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REDUCTION OF PARTICULATE EMISSIONS IN TURBINE ENGINES USING THE +100 ADDITIVE

ESTCP Project 200121

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14. ABSTRACT
The impacts on particulate and gaseous emissions from gas turbine engines using the Betz Dearborn Spec Aid 8Q462 (+100) thermal stability additive were evaluated. Emissions tests with and without the additive were conducted on two TF33 engines, two T-43 pilot trainer aircraft (AF equivalent to a B737) with JT8D-9A engines, and a T63 helicopter engine. Test results showed that the effects of the additive on emissions were dependent on the engine and power setting. For instance, measurable reductions (~20-25%) in particle number density (PND) were observed with the additive for the TF33 engine at a near cruise condition; however, negligible effects were observed for the other four conditions. For gaseous emissions, reductions up to 20% in total unburned hydrocarbons (THC) were observed for all conditions for the second TF33 engine tests. Similar gaseous emissions results were observed in the T63 tests. No evidence of improved particulate or gaseous emissions as a function of operation time with the additive was observed in the T63 long duration tests. For the first TF33 demonstration, chemical characterization of the particles showed increased concentration of polycyclic aromatic hydrocarbons (PAH) as a function of engine power with no significant impacts with the +100 additive. Reductions of up to 40% in PND were observed for one of the JT8D-9A engines with the additive; however, mixed results were observed for the other three.

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Abstract

The impacts on particulate and gaseous emissions from gas turbine engines using the Betz Dearborn Spec Aid 8Q462 (+100) thermal stability additive were evaluated. Emissions tests with and without the additive were conducted on two TF33 engines, two T-43 pilot trainer aircraft (AF equivalent to a B737) with JT8D-9A engines, and a T63 helicopter engine. Emissions were sampled at steady-state conditions for at least five power settings for each test. The particulate sampling and data acquisition were performed by the University of Missouri-Rolla (UMR) under subcontract with Boeing Corp. The gaseous emissions analysis was performed by Deposition Research Laboratory (DRL) and AFRL. The TF33 and T63 engines were internally inspected with a borescope to assess soot deposition and cleanup, and potential impact on particulate emissions. Also, chemical speciation of the particulate exhaust for the first TF33 engine was performed by scientists from the National Institute of Standards and Technology (NIST) to investigate the effects of the additive on the polycyclic aromatic hydrocarbon (PAH) content in the particles. In an attempt to assess long-term effects of the additive on emissions, the T63 engine was tested for 175 hours (87.5 hours on each fuel).

Test results showed that the effects of the additive on emissions were dependent on the engine and power setting. For instance, measurable reductions (~20-25%) in particle number density (PND) were observed with the additive for the TF33 engine at a near cruise condition; however, negligible effects were observed for the other four conditions. For gaseous emissions, reductions up to 20% in total unburned hydrocarbons (THC) were observed for all conditions for the second TF33 engine tests. Similar gaseous emissions results were observed in the T63 tests. No evidence of improved particulate or gaseous emissions as a function of operation time with the additive was observed in the T63 long duration tests. For the first TF33 demonstration, chemical characterization of the particles showed increased concentration of polycyclic aromatic hydrocarbons (PAH) as a function of engine power with no significant impacts with the +100 additive. Reductions of up to 40% in PND were observed for one of the JT8D-9A engines with the additive; however, mixed results were observed for the other three.

In summary, for most test cases considered the +100 additive had minimal effects on emissions and therefore, should not be considered as an additive to improve emissions. Measurable improvements were obtained for several conditions with the additive; however, since these were engine and power dependent its impacts on turbine engine emissions are difficult to predict. Despite the inconsistent effects of the additive on emissions, the demonstrated ability of the +100 additive to maintain engine parts clean (UTC & C4e, 2000) merit consideration to implement in these platforms. However, implementation costs, compatibility (for B-52) and logistic considerations should be assessed before the additive is implemented in these or other aircraft.

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1. Introduction

1. 1 Background

The United States military spends about $3.5 billion per year for aviation fuel. This corresponds to approximately three billion gallons of jet fuel per year (~10% of total US aviation fuel use). The fleet average emission index for particulate matter (PM) has been estimated to be approximately 0.04 g/kg of fuel burned. This means that 600,000 kg of particulates are emitted each year by US military aircraft alone (Landau et al., 1994; Thompson, 1996). Therefore, the total amount of particulate emissions for aircraft in the United States is about 3 million kg per year. The level of emissions from military engines corresponds roughly to 5×10^{24} particles per year with an average size of 50 nm diameter and an average density of 2 g/cm^3 (Howard, 1996). Although there is some uncertainty in these estimates, they are consistent with the magnitude being used to estimate global emissions from aircraft (Niedzwiecki, 1998). Airborne particles pose both health and environmental risks. The health effects of particular matter are related to its ability to penetrate the respiratory system. Fine particles, known as PM2.5 (<2.5 µm dia.) can enter the lungs and end up in lung capillaries and air sacs (alveoli) causing a variety of respiratory problems. In addition, particulate emissions contribute to environmental problems such as visibility impairment (haze), and it may contribute to increased signature (IR emissions) from military aircraft, increasing aircraft detectability/vulnerability in enemy territory. Furthermore, airborne particles form nucleation sites for condensation and complex chemical reactions that can lead to contrail formation (global warming) and ozone depletion at high altitudes. Gas turbine engines and ground support equipment are major local sources of PM2.5 particles. Essentially all of the solid particles in aircraft exhaust are PM2.5. Since most of these fine particles are carbonaceous, they are commonly referred to as soot in the combustion community. Due to the potential impact of particulate emissions on both the environment and human health, particularly for ground crews and other personnel working in close proximity to aircraft, it is important to find ways to reduce or eliminate PM2.5 emissions.

The health and environmental concerns from particulate emissions motivated this work to evaluate the use of the "+100" (BetzDearborn SpecAid 8Q462) additive in jet fuel as a means to reduce the particulate emissions from military gas turbine engines. The +100 additive was developed to increase the thermal stability of JP-8 fuel, i.e. to reduce carbon buildup in fuel system components as the fuel is heated. Mostly military aircraft (~3000) are currently using the +100 additive, however, the additive is also suitable for commercial aircraft due to the similarities of JP-8 and commercial Jet A.

1.2 Objectives of the Demonstration

The objectives of the demonstration were to evaluate the reduction in particulate and gaseous pollutant emissions from gas turbine engines using the +100 additive in JP-8. Testing was conducted on engines of military transport or bomber aircraft, a commercial-like aircraft and a helicopter engine. The cargo and bomber aircraft are estimated to burn over 70% of the jet fuel annually consumed by the military. Based on preliminary results, the Air Force could reduce particulate emissions by 126,000 kg per year by using the +100 additive in its transport aircraft. Using the +100 additive is a pervasive, cost-effective technology that can potentially reduce PM2.5 emissions from all military and commercial aircraft, gas turbine engines operated in test cells and for power generation for shipboard and ground support equipment. Furthermore, the

additive may be able to reduce other pollutant emissions from engines as they age and their efficiency declines. The use of an additive, which adds only ½ cent per gallon of fuel, presents a much more cost-effective solution than other pollution prevention measures such as redesigning or retrofitting an engine.

1.3 Regulatory Drivers

The National Ambient Air Quality Standards (NAAQS) have a health-based regulation for particulate matter with diameters less than 10 microns (PM10). The regulation limits exposure to air with PM10 concentrations greater than 150 micrograms per cubic meter ($\mu g/m^3$) in a 24-hour time period and an annual 24-hour exposure of no greater than 50 $\mu g/m^3$ (EPA Fact Sheet Dated November 29, 1996). There is growing evidence that this regulation is insufficient to eliminate serious health and environmental problems for particulate matter with diameters smaller than 2.5 microns (PM2.5). Indeed, the EPA has adopted a revision of the regulation for PM2.5 particles (EPA Fact Sheet dated July 16, 1997). The U.S. Supreme Court recently upheld the constitutionality of the Clean Air Act as interpreted by the EPA in setting the new PM2.5 particulates standard (EPA Fact Sheet dated February 27, 2001). One health concern is that these particles remain suspended in air and when inhaled lodge deep in the lungs where they cause a variety of health effects. In particular, fine particles are associated with increased respiratory symptoms related to lung disease and fatal illnesses. At least twelve separate studies have indicated that the concentration of airborne particles can be correlated with acute mortality (Dockery, 1982; Schwartz, 1993). The correlation is also size dependent, mortality increases and becomes more statistically significant as particle size decreases (Lippmann, 1985). Furthermore, this relationship appears to be linear without any evidence to date or of threshold concentration values (Wilson, 1996).

An extensive air quality monitoring network for PM2.5 is underway by EPA to determine which areas meet or do not meet the revised PM2.5 standards. After establishing PM2.5 attainment and non-attainment areas, the PM2.5 regulation is expected to take effect.

1.4 Stakeholder/End-User Issues

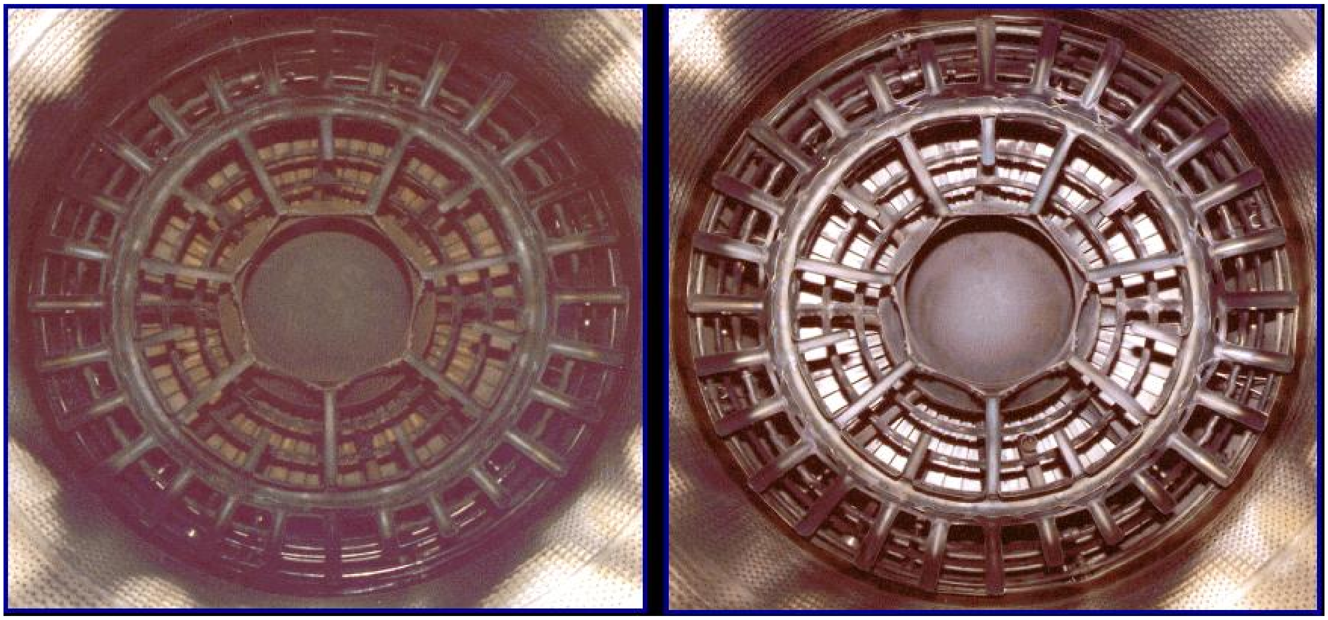
Demonstration of the benefits of the +100 additive in reducing particulate emissions from large transport aircraft will drive depot managers and stakeholders to implement the technology at their bases to improve quality of life for service members and surrounding communities and to comply with NAAQS regulations. In addition to the health benefits due to reduced PM2.5, the additive may also reduce maintenance in aircraft engines as has been observed in fighter and C-130 cargo aircraft using JP-8+100. Analyses of field data indicate significant reductions in fuel-related maintenance costs, and a three-fold increase in mean time between fuel-related failures (UTC & C4e, 2000). The +100 additive has been exhaustively tested to ensure compatibility with all materials currently used in turbine engines (Kalt, 2000). In fact, the additive has been tested more thoroughly than JP-8, the currently used Air Force aircraft fuel. Because of the thorough material compatibility testing and the field results to date, this additive has been certified by engine manufacturers General Electric and Pratt & Whitney for use in all Air Force engines. Additive approval from aircraft builders and depot managers (logistics and maintenance organizations) of large cargo aircraft will be critical to the successful transfer of this technology.

2. Technology Description

2.1 Technology Development and Application

The +100 additive is a fuel additive developed for use with JP-8 military fuel to improve its thermal stability by 100°F. Thermal stability is the ability of the fuel to resist carbon deposits in fuel systems upon heating. The +100 additive package consists of a detergent /dispersant, a metal deactivator, an antioxidant and a solvent (carrier). The additive package is added to JP-8 at a concentration of 256 mg/l resulting in JP-8+100. The improvement in thermal stability was necessary because modern aircraft use the fuel to cool a variety of aircraft subsystems. The cooling load applied to the fuel in many aircraft exceeded the thermal stability of the fuel causing carbon deposit formation in fuel lines and nozzles. These deposits increase the maintenance requirements and engine operation anomalies. The deposits also degrade engine performance and increase pollutant emissions.

The JP-8+100 development started in 1990 with investigations into the cooling requirements for current, next generation and future aircraft. Studies showed that a threefold increase in the heat-loads for future aircraft and aircraft subsystems compared to the F-4 was expected. Since the fuel is the primary heat sink of an advanced aircraft, a fuel that can operate at higher temperatures was needed in order to provide adequate heat sink and enable advanced aircraft technology development. To address this problem, a working group at WRDC (now AFRL) recommended the development of a high thermal stability fuel. The additive approach was selected since it is cost-effective and less logistically burdening than developing and fielding a new fuel. Hundreds of additives were tested for effectiveness using a variety of fuel test rigs (Heneghan, et. al 1996). In this manner, a novel high-thermal stability jet fuel was successfully developed. JP-8+100 is being used in over 3000 military aircraft in over 70 locations around the world. It is also being evaluated for use in commercial KLM 747 airplanes. After initial field testing of the +100 additive, several benefits were experienced. Analyses of field data indicated significant reductions in fuel-related maintenance costs, and substantial increases in mean time between fuel-related failures. In addition, the engine components appeared cleaner, with drastically reduced soot buildup (Figure 1). The increase in thermal stability with the +100 additive is mainly attributed to the detergent/dispersant. The dispersant is believed to prevent the agglomeration of carbon deposits or precursors formed during the heating of the fuel. This avoids the formation of large particles to help keep the oxidation products soluble in the fuel and off of fuel system component surfaces. Although fuel oxidation in a fuel system and during combustion are entirely different processes, a similar mechanism may help reduce the amount of particulate emissions in aircraft engine exhaust by reducing coagulation of particles or oxidized products formed during combustion. Furthermore, the +100 additive will help keep engine components clean, particularly the fuel nozzles, which is likely to improve emissions since the engine operates as designed. Keeping the fuel nozzles clear of carbon deposits helps ensure uniform fuel spray distribution for optimum engine performance. The cleaning effect of the +100 additive is also important for other emissions because as turbine engines age their efficiency decreases and pollutant emissions increase. As such, the +100 additive may prove an effective way of reducing gaseous pollutant emissions in addition to reducing particulate emissions. Another mode of action is a chemical effect in which the additive interferes with the formation or enhances the burnout of soot particles.



(a) (b)

Figure 1. F100 engine a) 200 hrs on JP-8, b) 200 hrs on JP-8 then 56 hrs on JP-8+100

2.2 Previous Testing of the Technology

In 1997, Boeing and the University of Missouri-Rolla (UMR) collaborated to study changes in particulate emissions after an engine had been transitioned to the +100 additive. Their study consisted of making particulate measurements on several F100-PW-100 in F-15A aircraft operating with and without the additive. After the aircraft had been running under standard operating conditions with the +100 additive for 97 hours, measurements of the particulate emissions were taken, (Figure 2 & Figure 3). A decrease between 20% and 35% in the PND emissions index with the engine operating on JP-8+100 compared to JP-8 was observed (Figure 2). As mentioned previously, the mechanism of this reduction is not fully understood. We postulate the reduction is due to maintaining the cleanliness of engine parts, thus improving system operation.

Shifting particulate matter (PM) size to smaller particles will help meet the new NAAQS PM2.5 standard since the resultant total mass of the PM will be lower.

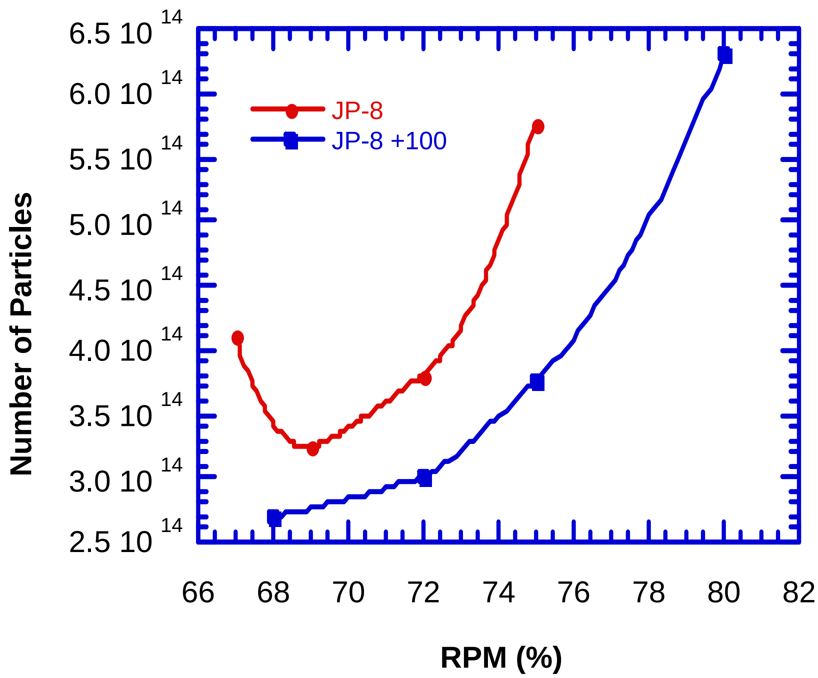


Figure 2. Boeing/UMR measurements of Particulate Number for F100 engine 680900. Emissions taken initially for JP-8 and after 97 hours running on JP-8+100.

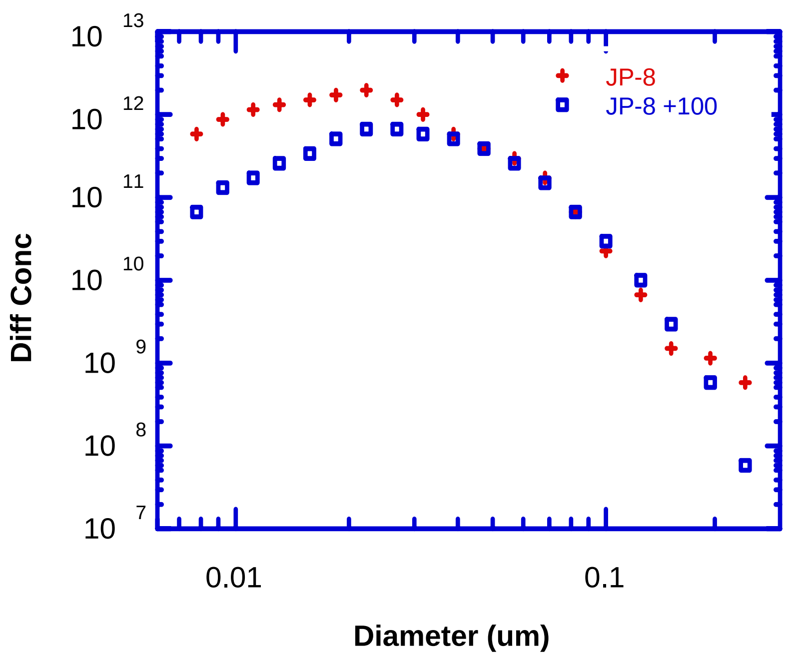


Figure 3. Size Distribution for Particulate Emissions for F100 engine 680900 at 68% RPM. Emissions taken initially for JP-8 and after 97 hours on JP-8+100

Recently, the United Technologies Research Center (UTRC) under an Air Force research program, conducted experiments to assess the effects of JP-8+100 on the production of particulate emissions from an F119 single nozzle combustor (Liscinsky, et al 2001). The combustor was operated at an air inlet temperature of 500°F and pressures to 200 psi and at several fuel-to-air ratios. As shown in Figure 4 and Figure 5, significant reductions in particle size, PND, smoke number and estimated mass were observed when the combustor was operated with JP-8+100. Reductions of 60-70% in the particulate mass and up to 40% in smoke number were observed. These data further support that the +100 additive may reduce particulate emissions from aircraft engines.

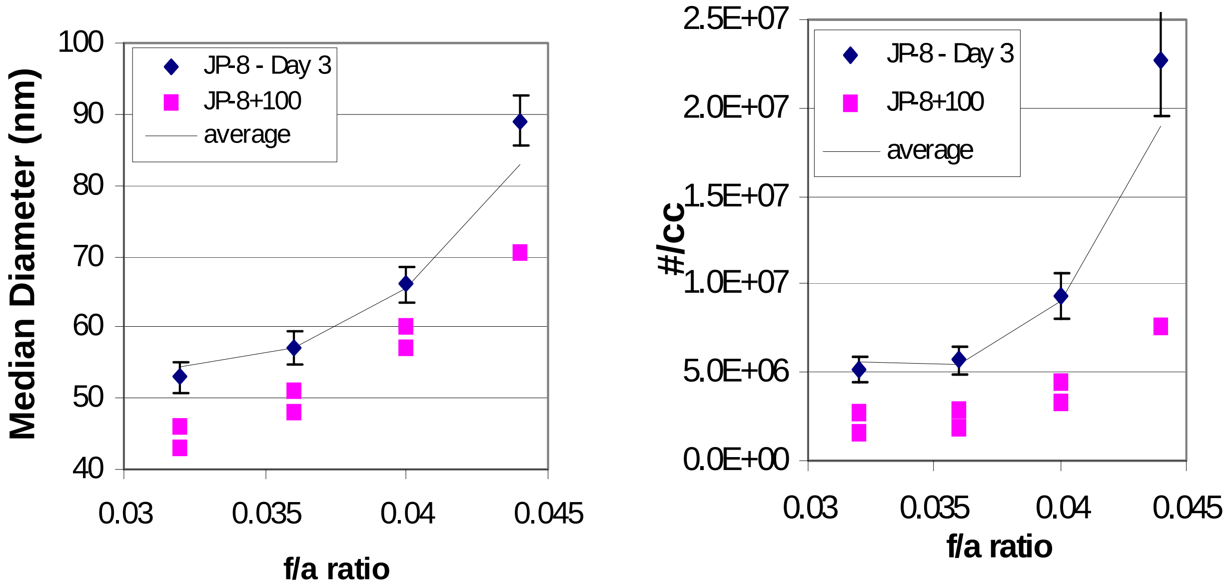


Figure 4. Effects of +100 additive on particulate diameter and PND

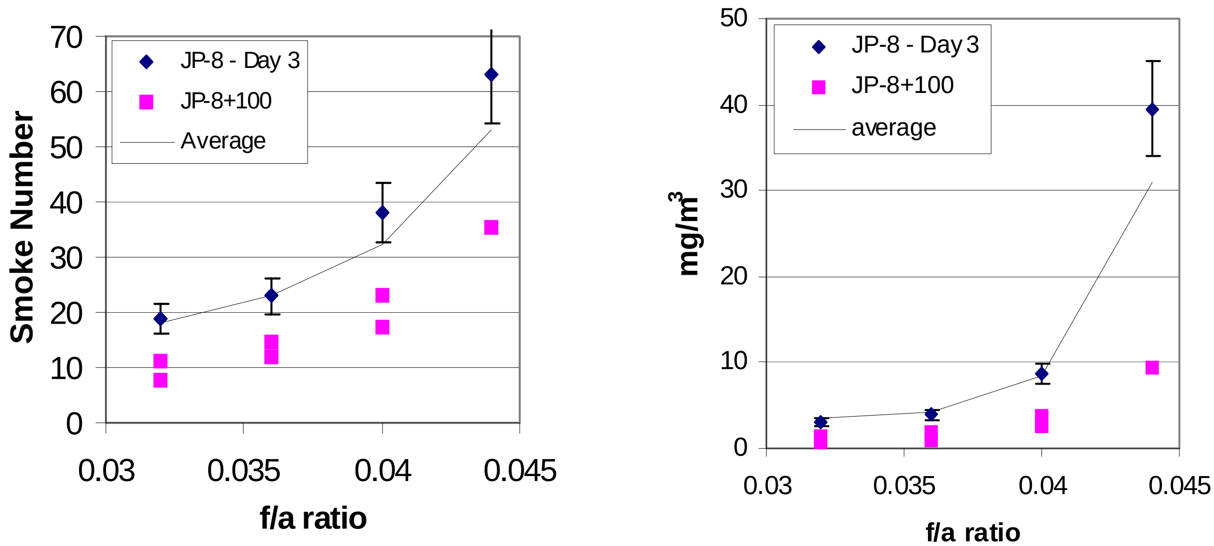


Figure 5. Effects of +100 additive on smoke number and particulate mass

2.3 Factors Affecting Cost and Performance

JP-8+100 is currently used in over 3000 military aircraft, mostly fighters and trainers. The cost of the +100 additive is approximately ½ cent per gallon of fuel. Demonstrating improvements in pollutant emissions with the additive will encourage additive buy-in and implementation by DOD depot managers and owners of transport and bomber aircraft. Furthermore, the same emissions benefits are expected in commercial engines due to the similarities between engines of transport and commercial aircraft, which will encourage additive implementation by the commercial airliners. Use of the additive in military transport aircraft alone will increase its production by a factor of three, which will very likely reduce the cost of the additive.

The concentration of particulate emissions from turbine engines is strongly dependent on several factors which include: engine technology, number of engine run hours (last maintenance cycle), quality and composition of the fuel used, fuel injector design and others. Particulate emissions also vary significantly depending on the engine operating condition. Since at idle the engine fuel consumption is lower, the soot particulate emissions are expected to also be lower, however, the total unburned hydrocarbons (THC) emissions are expected to be higher due to less efficient fuel nozzles and engine performance. Furthermore, the concentration of volatile particulate emissions is expected to be higher at idle because of the increased THC. Soot particulate emissions will increase as engine power is increased due to the higher fuel consumption, however, THC levels (and volatile particulate fraction) should be lower due to improved atomization and combustor efficiency at higher fuel flow rates. It is uncertain at which engine condition the additive will have the greatest impact, however, it is expected that the additive will have some degree of improvement in engine emissions at all engine power levels.

2.4 Advantages and Limitations of the Technology

Fuel additives are the most cost-effective means of improving fuel characteristics and combustion performance in combustion systems. Fuel additive technology has been used for many years in aviation and automotive applications to improve ignition, pollutant emissions, cold flow characteristics, engine performance, fuel lubricity, fuel safety and fuel efficiency. The +100 additive has been demonstrated to reduce aircraft engine maintenance due to fuel related (coking) problems. Developing additives to treat JP-8 is logistically more favorable than reformulating a new fuel. It follows the US military goal of a single fuel for the battlefield. Other ways of improving pollution emissions from combustion systems, i.e. engine redesign and/or retrofit, are cost prohibitive and labor intensive.

Although additive technology is the most cost-effective and a near term solution to emissions concerns, it does have its limitations. Since the JP-8 specification limits are quite wide, particularly in aromatic and sulfur content, the effectiveness of the +100 additive may not be equal for all JP-8 fuel batches. However, the fuel composition will appear to affect the performance of the additive only if the +100 affects the combustion chemistry. If the +100 benefits are due to cleaning and/or maintaining fuel nozzles free of soot to produce optimum engine operation, then more pronounced effects are expected with the +100 additive for lower quality fuels.

Concerns exist about the use of the +100 additive in large aircraft because of the defueling operations these undergo in bases that are not equipped to handle the additive. There is evidence that the dispersant in the +100 additive package disarms existing filter coalescers. That is, the

coalescers work inefficiently causing poor fuel-water separation. With funding from AFRL/PRTG, improved filter coalescers for use with the +100 additive have been developed. An efficient implementation of these filters has not taken place; however, successful demonstration of the +100 additive to reduce particulate emissions will encourage the implementation of the new filter coalescers and full implementation of the +100 additive at bases with large aircraft.

3. Demonstration Design

3.1 Performance Objectives

Table 3.1 presents the quantitative and qualitative performance objectives of the demonstration, the test metrics and assessment of the actual performance. The magnitude of reduction of 40% or larger was selected to ensure statistical significance based on prior experience.

Table 3-1. Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (metric)	Actual Performance Objective Met?
Quantitative	1. Reduce particle number density by 40% with JP-8+100. 2. Reduce PM mass concentration by 40% when using JP-8+100.	1. Reduced particle number density by 30-50% with JP-8+100. 2. Reduced PM mass concentration by 30 - 50% or higher when using JP-8+100.	1. In general, performance objectives were not met for PND or mass. Mixed results depending on engine and engine condition.
Qualitative	1. Reduce soot buildup in engine compared to operation with JP-8.	1. Reduced engine maintenance costs.	Not possible to assess due to short duration of additive use. Additive was only used during the evaluation.

3.2 Selecting Test Platforms/Facilities

Three test sites were used for the demonstration of the +100 additive technology to reduce particulate emissions. The facilities were: the Air Education and Training Command (AETC) 12th Flying Training Wing at Randolph, AFB Texas, the T-9 test facility at Barksdale AFB Louisiana, and the Environmental Engine Research Facility at Wright-Patterson AFB Ohio. A summary of the engines or aircraft tested is shown in Table 3.2. A description of the work performed at each test site is discussed in the next section.

Table 3-2 Demonstration Sites

Engine or Aircraft	Location
TF33 engine	Barksdale AFB, LA
T-43A aircraft	Randolph AFB, TX
T63 engine	Wright-Patterson AFB, OH

3.3 Test Platform/Facility History/Characteristics

Both the engine-on-wing and static-engine emissions tests consisted of operating the engines at various power settings and measuring particulate and gaseous emissions with the engine fueled with and without the +100 additive. A description of the test venues is given below.

Randolph AFB, TX
Randolph AFB was a convenient location because the base had already been converted to use the +100 additive. In addition, it flies training missions; therefore, the majority of the aircraft flights originate and terminate at Randolph. As such, it was very likely that the aircraft emissions assessment with and without the +100 additive could be accomplished using the same aircraft. Furthermore, concerns with defueling JP-8+100 from the aircraft at bases not converted to +100 were eliminated since the aircraft returned to Randolph. The T-43A was the selected aircraft for the demonstration. The T-43A is the military version of the commercial Boeing 737. It is powered by two Pratt & Whitney JT8D-9A engines and is used for pilot and navigator training. The AF has a total of ten T-43As, all of them stationed at Randolph AFB. Representatives from Boeing, the T-43 SPO and Pratt & Whitney were contacted and informed of the planned demonstration. Boeing, a strong supporter of this program, pursued and received certification of the aircraft for use of JP-8+100. Pratt & Whitney had already certified the JT8D-9A engine for JP-8+100. A T-43A program review took place in August 2002 where the T-43 SPO was formally briefed the test program. During such meeting, the T-43 SPO and Boeing approved the proposed JP-8+100 demonstration on the T-43. This demonstration was the only engine-on-wing conducted under this program.

Barksdale AFB, LA
The T-9 test cell at Barksdale AFB is an ACC owned and operated facility used to test the B-52's TF33 engines. It is used mainly to evaluate engine EGT (Exhaust Gas Temperature), vibration and engine intake characteristics to ensure sound operational capability before installing on the aircraft. A picture of the engine test stand at Barksdale is shown in Figure 6. In this facility two TF33 engines, tested 18 months apart, were evaluated to study the efficacy of the additive to reduce emissions at various operating conditions. The engines were operated at five power settings to measure particulate and gaseous emissions throughout the engine's operating regime. Also, for the first test series the National Institute of Standards and Technology (NIST) performed chemical characterization of the particulate emissions at various engine conditions to assess effects of the additive on the concentration of carcinogenic PAHs in the emitted particles. This characterization provided data in a realistic environment to aid in the development of a standard methodology to chemically characterize particulate emissions from aircraft. This chemical speciation effort was funded by AFRL/PRTG.

Figure 6 Engine test facility at Barksdale AFB

T63 Engine Wright-Patterson Air Force Base

A T63-A-700 turboshaft engine, employed primarily in helicopter applications, was used to evaluate the long-term effects of the additive. The engine is located in the Engine Environment Research Facility (EERF) in the Propulsion Directorate at Wright-Patterson Air Force Base (WPAFB), and is used to evaluate turbine engine lubricants, fuels, and sensors in an actual engine environment. These tests were conducted and the data analyzed by WPAFB and University of Dayton Research Institute (UDRI) scientists. A picture of the T63 engine is shown in Figure 7.

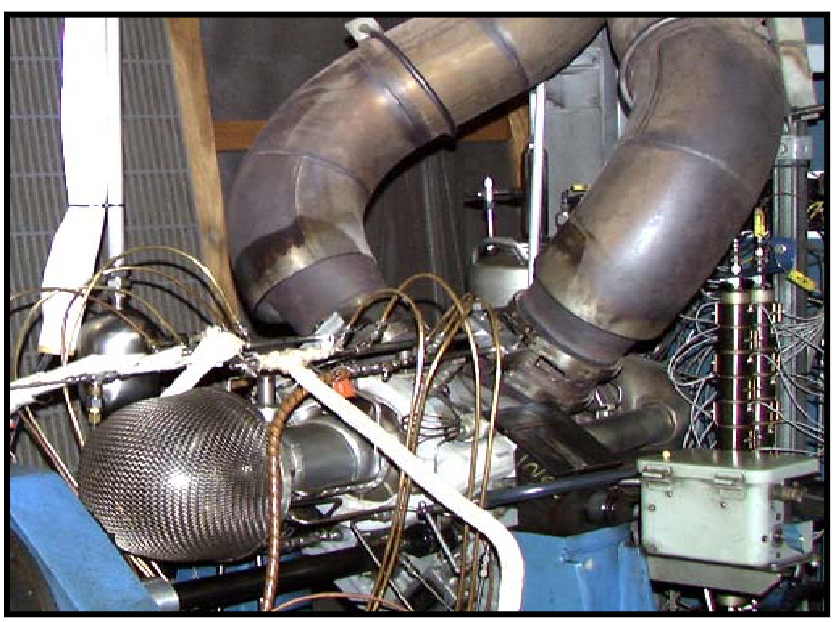


Figure 7. T63 Engine at WPAFB

3.4 Present Operations

The main approach to address pollutant emissions from turbine engines is to develop advanced turbine engine technologies to provide more efficient and environmentally friendly engines. Regarding fuels, DoD has been studying the feasibility of reducing the sulfur levels in the JP-8 specification from 3000 ppm to 500 ppm. Since the mean sulfur level in JP-8 produced today is ~490 ppm, reducing the sulfur to 500 ppm levels is expected to marginally reduce SO_x and particulate emissions (sulfates) without compromising fuel supply and cost. However, this reduction in particulates may not be sufficient to comply with the new regulation of fine particulate matter. Furthermore, a reduction in sulfur content in the fuel is not expected to affect soot particulates, which are believed to be the most abundant solid particulates (non-volatile) emitted from aircraft. The upcoming EPA PM2.5 regulation will increase pressure on DoD agencies to also address particulate emissions and develop means to mitigate this pollutant from aircraft engines.

3.5 Pre-Demonstration Testing and Analysis

Baseline (JP-8) particulate measurements were taken for engines in test cells and aircraft engines on the runway. The tests consisted on operating the engines with JP-8 at a minimum of five conditions from idle to higher power. Sufficient particulate and gaseous emissions data were taken to ensure statistical significance. After completing the sweep of conditions, the engine was brought back to idle and the procedure was repeated. Repeated sweeps or cycles provided independent points at each condition for each fuel to assess uncertainty in the data. After conducting the baseline tests, the engines were fueled with JP-8+100 and the procedure repeated.

3.6 Testing and Evaluation Plan

3.6.1 Demonstration Set-Up and Start-Up

Several weeks prior to the demonstration or when necessary, the demonstration team conducted a site visit to the test facility or base to discuss the final test plan and to address any special needs or concerns with the tests. Usually two days prior to the demonstration, the research team met at the test location and started the equipment setup. The first day of the demonstration the systems were ready for calibration, background sampling and system check-up. After ensuring the measuring systems were operating properly, the facility or aircraft operators were contacted to start the tests. The engine was operated at different conditions and the exhaust was sampled for analysis.

3.6.2 Period of Performance

The period of performance was between March 2002 and April 2004.

3.6.3 Amount/Treatment Rate of Material to be Treated

JP-8 fuel was treated with 256 mg per liter of fuel (roughly 1 liter additive per 1000 gallons of fuel) to convert to JP-8+100. The amount of fuel treated depended on the engine tested, and the engine run time needed to acquire the data at each condition. JP-8 and the +100 additive were mixed in an external tank (Barksdale tests), injected online (T63 tests) or injected prior to entering the aircraft fuel tanks (T-43 tests). These blending techniques avoided contamination of the underground fuel tanks with the additive, thus preventing any concerns with disarming the current filter coalescers.

3.6.4 Operating Parameters for the Technology

Various parameters including particle number density (PND), particle size distribution, gaseous emissions and particulate PAH content (TF33 Test I) were monitored and analyzed to assess the effectiveness of the additive to reduce pollutant emissions. The PM measurements in the field were performed by UMR using a suite of advanced instrumentation housed in its MASS (Mobile Aerosol Sampling System) trailer. The various instruments and techniques used for these measurements are briefly described below.

3.6.4.1 PND was measured with a condensation nuclei counter (CNC). The CNC provided real-time measurements of the number of particulates per cubic centimeter sized between 7 – 3000 nanometers (nm) in diameter exiting the engine. A statistical analysis of the CNC data was conducted to determine the standard deviation and the uncertainty of the measurement.

3.6.4.2 Due to the large dynamic range involved in the aerosol size, two measurement techniques were used for different regimes of particle size. For particles with diameters smaller than 300 nm, the particle size distribution was determined using a Differential Mobility Analyzer (DMA). The DMA classifies the particles in different diameters by their mobility through an electric field. Shifts in the particulate size distribution using the additive may indicate that the additive has changed the inception, coagulation or particle oxidation characteristics.

3.6.4.3 For particles with larger diameters (>300 nm) a Laser Particle Counter (LPC) was used. This instrument uses a light scattering technique to count the particles. The larger particles were measured to also assess if the additive changed the coagulation characteristics of smaller particles to form larger particles.

3.6.4.4 A simplified schematic of UMR's MASS is shown in Figure 8. Particle-laden air was extracted directly from the combustor/engine exhaust flow through a particulate probe and supplied to the particulate measurement devices. In general, the CO_2 and standard combustion gas analysis bench station received sample air through a separate gas probe in order to avoid interference with the particle measurements. The total dilution of the particulate sample was determined by comparing the CO_2 concentrations from the undiluted gas probe to those diluted concentrations measured in the particulate probe. Clean (particle free), dry dilution air was added to the particulate sample flow at or near the probe tip in order to quench chemical reactions, and to minimize particle-to-particle interaction (e.g. coagulation), and gas-to-particle conversion (nucleation, condensation). In high particle number density cases, a second clean air dilution was introduced within one meter of the sampling orifice. The sample was transported through a line (heated to 150°C when necessary) (heavy solid line in Figure 8) from the probe to the main section of the MASS. The elevated temperature of the transport line further reduced the risk of

nucleation/condensation by keeping the saturation ratio with respect to water and/or semi-volatile gas phase components low. Upon entering the trailer-housed section of the MASS, the sample was allowed to cool from 150°C to room temperature. The total sample flow was split with 0.5 slpm being diverted into a laser particle counter (LPC) acquiring real-time coarse particle size distributions (> 700nm). The LPC was located as close as possible to the source with supply lines with large radii of curvature to minimize coarse particle loss. A tube-type diffusion battery removed small particles with a 50% cutoff at 100 nm. Immediately downstream of the LPC the sample aerosol was neutralized with a bipolar charger containing four radioactive ^{210}Po elements (500 μCi each; ∀-emitter) to minimize wall losses in transport lines. Subsequently, the sample flow was split into several flows, which were subjected to simultaneous measurement of PND, fine particle size distribution (< 700 nm), particle morphology (electrostatic precipitator, TEM), and dew point, flow rate, pressure and temperature (the three latter are not shown in Figure 8). Significant changes in the size (surface area, mass) of soot particles have been observed for relative humidities exceeding about 40 % due to restructuring and deliquescence processes, therefore, the relative humidity of the sample was monitored with a hygrometer and regulated to values below 40 % by adjusting the amount of dilution air.

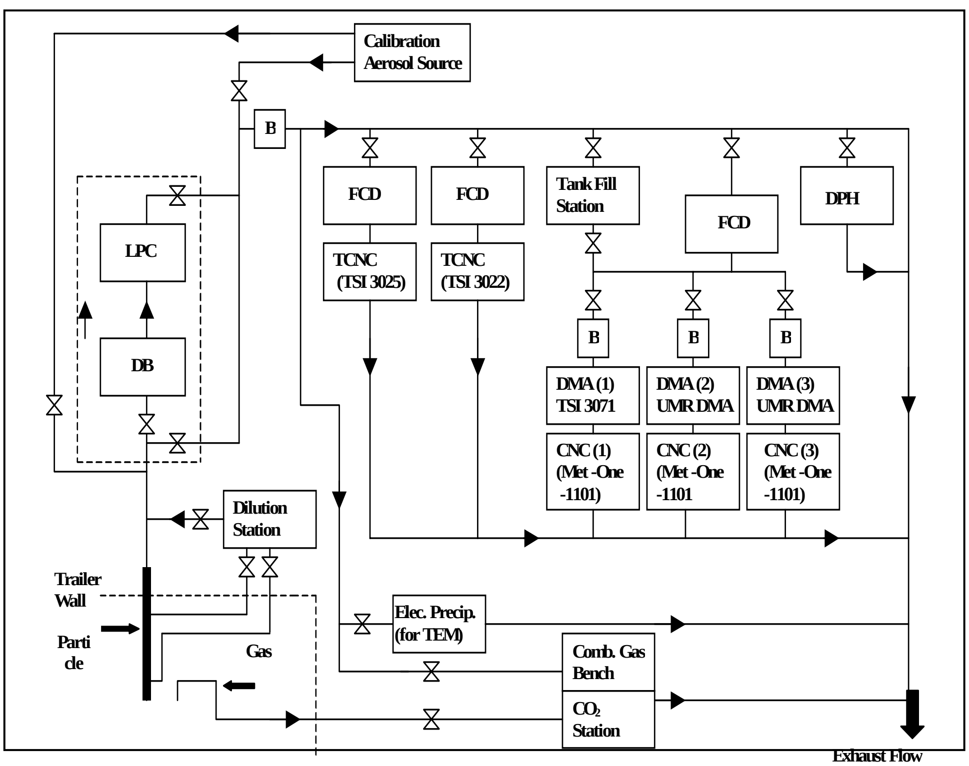


Figure 8. UMR Mobile Aerosol Sampling System Flow Diagram

3.6.4.5 In the first TF33 engine tests, NIST conducted analysis to determine the concentration of liquid phase PAHs condensed on the particles, and the gas phase PAHs. PAHs are known carcinogens easily trapped by fine particles that can easily get into the blood stream and enhance cancer inductors. Soot samples were collected in quartz filters and the PAH extracted from the filters by pressurized-fluid extraction using dichloromethane as the solvent. The amount of PAHs was quantified using gas chromatography/mass spectrometry (GC/MS). The samples were fortified with perdeuterated PAHs to serve as internal standards. It has been demonstrated that the typical uncertainty in this measurement method is +/- 3 % of the measured value. The result of this phase of the study was the PAH concentration distribution for each engine condition, and an assessment of the effect of the additive on the PAH concentrations.

3.6.4.6 Gaseous emissions measurements were usually performed by Deposition Research Laboratory (DRL) using standard SAE aerospace recommended practices (ARP). The sample was acquired using a single, water-cooled probe, and was usually analyzed neat (not diluted) to stay within the measurement range of the instrumentation. The gaseous species measured include: CO_2, CO, total unburned hydrocarbons (THC), SO_x, and NO_x. The CO_2 measurement was also used by UMR to verify its dilution flow measurement to the particulates' probe and to relate the particulate data to the amount of fuel consumed. For Barksdale AFB Tests II, WPAFB scientists measured the gaseous emissions using an FTIR-based gas analysis system. The system is further described in Section 4.3.3.5.

3.6.5 Experimental Design

In order to demonstrate the effectiveness of the +100 additive to reduce particulate emissions from aircraft engines, a relatively large number of engines with and without the additive needed to be tested. In addition, instrumentation and sampling artifacts that may lead to ambiguous results needed to be addressed. Factors such as: different fuel batches, sampling probe and probe location, sampling system artifacts, different instrumentation settings (sample dilution, dilution air temperature, etc.), particulate matter from the facility, and soot particulates already in the engine, if not controlled could lead to data misinterpretation. Also, atmospheric conditions such as ambient temperature, pressure and humidity were monitored through the test period since these could affect engine particulate exhaust. For all tests, to the extent possible, tests were conducted with the same fuel batch and using the same probe and instrumentation settings. In order to account for the effects of testing with different JP-8 fuels, most fuels were characterized via ASTM JP-8 specification tests mainly to determine the sulfur and aromatic concentrations. Additionally, for various tests the fuels were characterized in laboratory engine experiments to estimate the effects of batch-to-batch variability of JP-8 on emissions. The

combustion tests consisted of testing these fuels in a T63 helicopter engine and performing particulate and gaseous measurements. These evaluations helped to avoid misattribution of changes in particulate emissions to the additive. Details of each demonstration test plan are described in section 4.3.

Particulate emissions samples were taken using the well-accepted AEDC/NASA designed particulates probe. The rake was located within ½ nozzle diameter to follow ICAO recommended practices for gaseous emissions sampling of turbine engine exhaust. Field test images of a previous test program performing particulate measurements on a C-130 aircraft are shown in Figure 9.

Figure 9. Single point particulate sampling probe at engine exit of C-130 aircraft (*tests conducted under a previous program*)

3.6.6 Product Testing

The testing methodology has been designed to unambiguously determine the effects of the +100 additive on particulate exhaust of different classes of turbine engines. EPA lacks a standard methodology for measuring fine particulates from aircraft engines. Smoke number has been used for many years as a standard for engine certification; however, this method only accounts for the large particles in the exhaust and is not well correlated to the fine particles (PM2.5) of interest in this evaluation. The instrumentation used in this project are the state-of-the-art in particulate characterization systems, and the individuals acquiring and analyzing the data are world-class experts with extensive field experience in making particulate measurements from aircraft. The tests were conducted maintaining close control on all parameters (e.g. dilution flow, sample flow, probe location) to minimize test variables and ensure that the baseline and the JP-8+100 tests were conducted using the same settings.

In cases where "zero-time" (clean) engines could be obtained for the engine stand tests, these will be first tested with JP-8+100 and then with the baseline fuel. In the field it has been observed that +100 cleans sooty engines. Therefore, if tested initially with JP-8 the engine will accumulate soot deposits, which will then be "washed off" when tested with JP-8+100. This will likely cause a temporary increase in the particulates exiting the

engine, which can be attributed to the cleaning process and not to the generation of particles with the treated fuel.

3.6.7 Demobilization

At the conclusion of the demonstration the sampling lines, test equipment, and probe stand were removed and the equipment was loaded on a truck and removed from the test premises. Any JP-8+100 left in fuel tanks was burned in the engine. Any +100 additive or additive containers were shipped back to WPAFB and disposed using established procedures.

3.6.8 Health and Safety Plan

Previous studies have shown that the +100 additive does not add any acute toxicological hazards to JP-8 (Kinkead et al, 1996). Since there are no known special safety issues associated with handling JP-8+100, fuel handlers employed the same safety procedures as used for handling conventional JP-8. During the initial site visit, safety issues were addressed with facility and base operators and a safety plan was generated. This was reviewed by facility personnel and made available to personnel participating in the tests. Every test day prior to starting the tests, scientists, engineers and technicians were provided with verbal safety procedures by the facility personnel in which test site practices, procedures and exit routes in case of an emergency were discussed. These helped ensure the safety of all test personnel during and after the tests were completed.

3.7 Selection of Analytical/Testing Methods

The test methodology used is based on the widely accepted UMR technique (described in Section 3.6.4) that measures various physical characteristics of the engine's particulate exhaust. By evaluating the PND, particle size distribution, and in the case of the Barksdale tests, chemical composition of the particles (with NIST), we can determine if the additive is affecting the formation or oxidation of particles, and content of harmful chemicals in the particulate emissions.

3.8 Selection of Analytical/Testing Laboratory

The engine test cells and Air Force facilities were selected to provide a flexible and realistic environment to evaluate the engines with and without the +100 additive. Engines tested are used in transport/cargo and bomber aircraft. A picture of the T-43 is shown in Figure 10.

Figure 10. T-43 Pilot and Navigator Trainer Aircraft at Randolph AFB TX

4. Performance Assessment

4.1 Performance Criteria

The performance criteria for the current demonstration are shown in Table 4-1. The particle concentration (PND) was designated as the only primary criterion because it was considered the best metric for the demonstration. A 40% or higher reduction was selected to ensure statistical significance based on previous experience. Due to the complexities associated with combustion processes in turbine engines, it was unrealistic to expect a significant reduction in particulate emissions with the additive for all engines and test conditions. Therefore, a 40% or larger reduction in PND for 70% or more of the test conditions was considered reasonable to confirm the reduction in particulate emissions with the additive.

Table 4-1. Performance Criteria

Performance Criteria	Description	Primary or Secondary
Reduced PM emissions	40% or larger reduction PND for 70% or higher for all tests	Primary
Reduced gaseous pollutant emissions	20% reduction in CO, NO_x and THC emissions for all test conditions	Secondary
Reduce size of PM	30% reduction in mean particulate diameter	Secondary
Reduced amount of PAH	50% reduction in PAH concentration on particulate matter	Secondary
Visibly cleaner engine	Cleaner turbine blades and exhaust	Secondary

4.2 Performance Confirmation Methods

The performance confirmation methods and actual performance parameters are listed in Table 4-2. As shown, most performance criteria were not met in this demonstration. Only a reduction of nearly 20% in THC was observed with the additive for two of the demonstrations (T63 and TF33 II). Other gaseous pollutants and PAH concentrations in the particulate samples were unaffected by the additive. Detailed results of each demonstration are described in the next sections.

Table 4-2. Performance Confirmation Methods

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual Performance
Reduced PM emissions	Greater than 40% in PM number density for 70% of tests	Average CNC measurements and determine uncertainty for each condition.	Only one case showed a maximum of 40% reduction in PND.
Reduced gaseous pollutant emissions	20% reduction in CO, NO_x and THC for all test conditions	Average gaseous emissions measurements and determine uncertainty for each condition	Additive reduced THC by 15-22% in TF33 & T63 engines. It had statistically insignificant effects on all other gaseous emissions. No effect observed on JT8D-9A engines.
Reduce size of PM	30% reduction in mean particulate diameter	Average particulate mean size measurements from DMA and determine uncertainty for each condition	Minor reductions in particle mean diameter.
Reduced amount of PAH	50% reduction in PAH concentration on PM	Average concentration of PAHs in particulates and determine uncertainty for each condition	Additive showed no effect on PAH content of particulates.
Visibly cleaner engine	Cleaner hot section/exhaust	Reduced engine maintenance. Compare images (photos) before and after tests {longer term (tenths of hours) effect}	Engine maintenance could not be assessed due to short-term use of the additive.

4.3 Data Analysis, Interpretation and Evaluation

Four (4) demonstrations were completed under this ESTCP program to assess the efficacy of the +100 additive to reduce particulate emissions from turbine engines. The demonstrations were:

1. T-43 aircraft (four engines) at Randolph AFB
2. TF33 engine at Barksdale AFB
3. Second TF33 engine at Barksdale AFB (TF33 II)
4. T63 engine at Wright-Patterson AFB

All engines under this demonstration program, except the T63, were tested at a minimum of five power settings with and without the +100 additive. PND, particle size distribution and fuel chemical composition were analyzed. Each engine power setting was held 5 to 10 minutes to ensure steady-state operation and gather sufficient data for statistical analysis. Several size distribution measurements were taken at each power setting to ensure particle size consistency throughout the period.

4.3.1 TF33 Tests I at Barksdale Air Force Base

4.3.1.1 Description and Objectives

Gaseous and particulate emissions measurements were performed on a single TF33 (B-52H (Figure 11) engine) engine at test cell T-9 at Barksdale, AFB. In addition to PND, size distribution and gas emissions measurements, the National Institute of Standards and Technology (NIST) (under contract with AFRL) chemically characterized the particulates to determine effects of engine power setting and the +100 additive on PAH constituents in the particles. The test plan for the TF33 engine tests is shown in Table 4.3.

Tests were conducted using JP-8 fuel as the baseline, which was then treated with the +100 additive. The test setup is shown in Figure 12. Measurements were made at two probe positions equally spaced from the engine centerline and near the center of engine air flowpath to obtain a representative sample of the engine core flow and assess the uniformity of the particulate emissions in the exhaust (Figure 13). The probe rake was located within ½ nozzle diameter aft the nozzle to follow the ICAO guidelines for gaseous emission measurements. Although it would have been ideal to start with a clean engine, we were limited to what the base could provide. Starting with a clean engine would have ensured that the particulate emissions measured from the initial tests were "real-time" combustion products and not residual soot particles left in the engine from previous operation.

Figure 11. B-52 Aircraft during take-off at Barksdale AFB

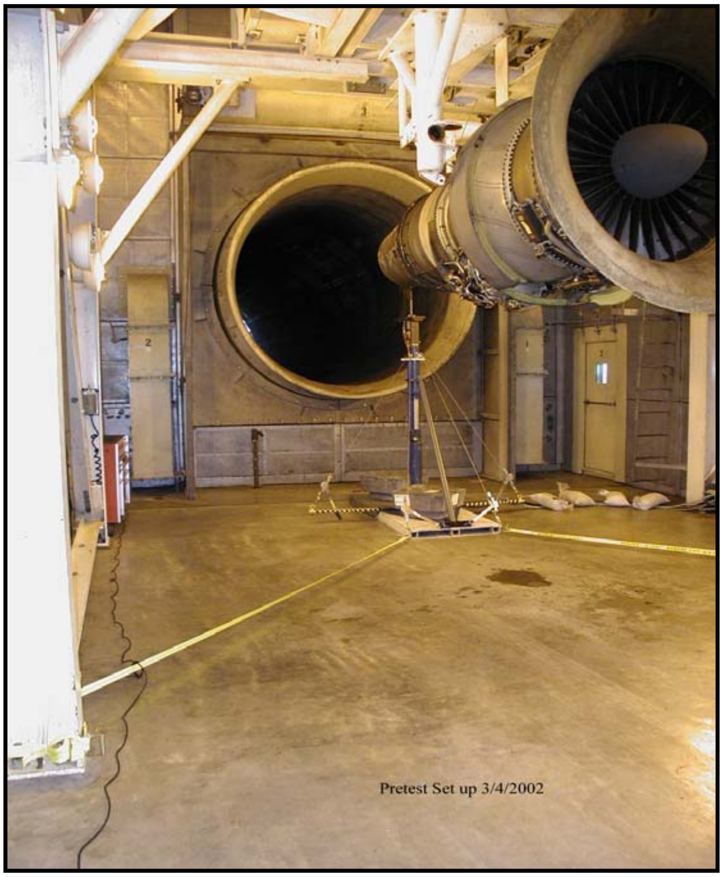


Figure 12. Particulate Emissions Rake setup for tests I at Barksdale AFB

Table 4-3. TF33 Test Matrix I

Run No.	Fuel	Probe Location	Engine %	Run Time (minutes)
1	JP-8	1	58	15
2	JP-8	1	70	15
3	JP-8	1	80	15
4	JP-8	1	90	15
5	JP-8	1	98	5
6	JP-8	1	58	15
7	JP-8	1	70	15
8	JP-8	1	80	15
9	JP-8	1	90	15
10	JP-8	1	98	5
11	JP-8	1	58	15
12	JP-8	1	70	15
13	JP-8	1	80	15
14	JP-8	1	90	15
15	JP-8	1	98	5
16	JP-8	1	58	15
17	JP-8	1	70	15
18	JP-8	1	80	15
19	JP-8	1	90	15
20	JP-8	1	98	5
21	JP-8	2	58	15
22	JP-8	2	70	15
23	JP-8	2	80	15
24	JP-8	2	90	15
25	JP-8	2	98	5
26	JP-8	2	58	15
27	JP-8	2	70	15
28	JP-8	2	80	15
29	JP-8	2	90	15
30	JP-8	2	98	5
31	JP-8	2	58	15
32	JP-8	2	70	15
33	JP-8	2	80	15
34	JP-8	2	90	15
35	JP-8	2	98	5
36	JP-8	2	58	15
37	JP-8	2	70	15
38	JP-8	2	80	15
39	JP-8	2	90	15
40	JP-8	2	98	5
41	JP-8+100	2	58	15
42	JP-8+100	2	70	15
43	JP-8+100	2	80	15
44	JP-8+100	2	90	15
45	JP-8+100	2	98	5
46	JP-8+100	2	58	15
47	JP-8+100	2	70	15
48	JP-8+100	2	80	15
49	JP-8+100	2	90	15
50	JP-8+100	2	98	5
51	JP-8+100	2	58	15
52	JP-8+100	2	70	15
53	JP-8+100	2	80	15
54	JP-8+100	2	90	15
55	JP-8+100	2	98	5
56	JP-8+100	2	58	15
57	JP-8+100	2	70	15
58	JP-8+100	2	80	15
59	JP-8+100	2	90	15
60	JP-8+100	2	98	5
61	JP-8+100	1	58	15
62	JP-8+100	1	70	15
63	JP-8+100	1	80	15
64	JP-8+100	1	90	15
65	JP-8+100	1	98	5
66	JP-8+100	1	58	15
67	JP-8+100	1	70	15
68	JP-8+100	1	80	15
69	JP-8+100	1	90	15
70	JP-8+100	1	98	5
71	JP-8+100	1	58	15
72	JP-8+100	1	70	15
73	JP-8+100	1	80	15
74	JP-8+100	1	90	15
75	JP-8+100	1	98	5
76	JP-8+100	1	58	15
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78	JP-8+100	1	80	15
79	JP-8+100	1	90	15
80	JP-8+100	1	98	5
81	JP-8+100	1	58	15
82	JP-8+100	1	70	15
83	JP-8+100	1	80	15
84	JP-8+100	1	58	15
85	JP-8+100	1	70	15
86	JP-8+100	1	80	15

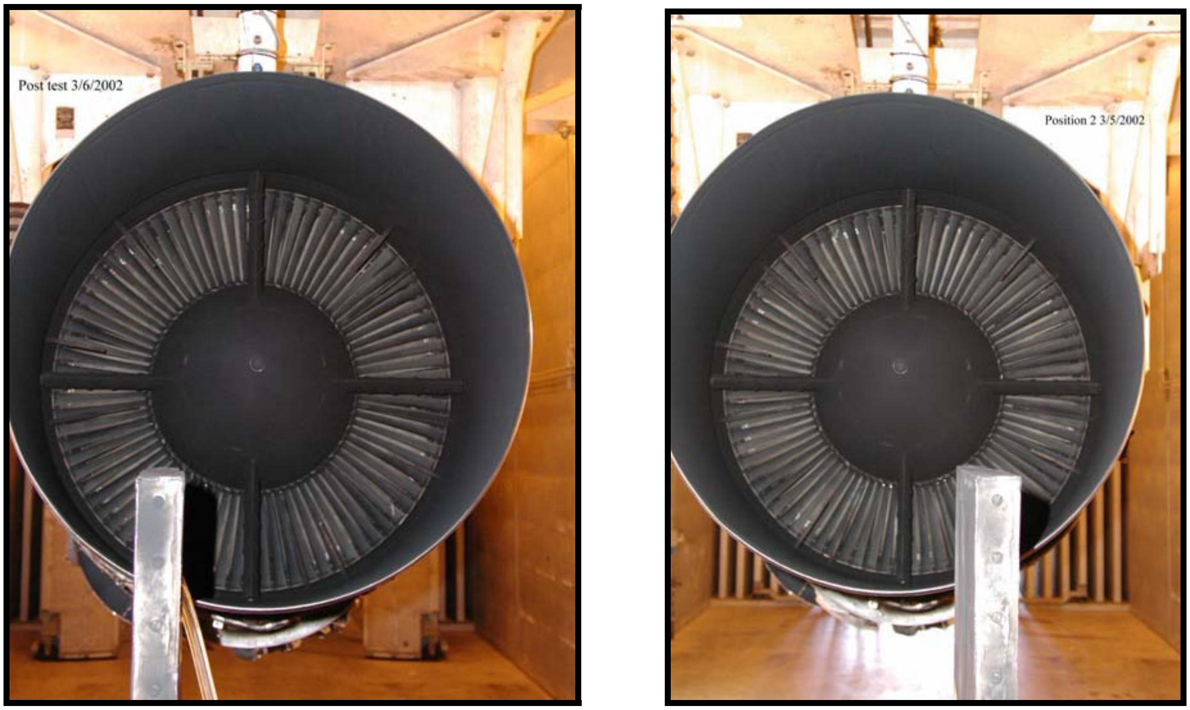


Figure 13. Particulate probe at two positions to assess uniformity of TF33 engine emissions

4.3.1.2 Chemical Characterization of Particulate Emissions from TF33 engine

Chemical characterization of the particulate emissions from the TF33 engine was conducted by NIST for all power settings tested. The sampling and analysis technique, described in detail in Section 3.6.4.5, captured the particulate sample via a water-cooled probe and collected the particulate volatile and non-volatile fractions in several filters. The PAH compounds were then extracted with a solvent for chemical analysis. Over 25 soot samples were collected for analysis. The major PAH components found on the soot samples as a function of power setting are shown in Figure 14. As shown, the idle condition (58%) produced almost two orders of magnitude larger concentrations of two-ring compounds and the lowest concentration of most four- and five-ring compounds. As the engine power level increased, the production of larger PAH also increased. The higher concentration of larger PAHs is directly associated with the increased pyrolytic reactions occurring at the higher temperatures found at high power. Most of the PAHs were found in the volatile (vapor phase) fraction of the sample. Production of three- and four-ring PAHs were similar for all power settings and much higher (30 to 100X) than the five-ring PAHs detected. Negligible effects of the additive on the PAH content on the collected particles were observed.

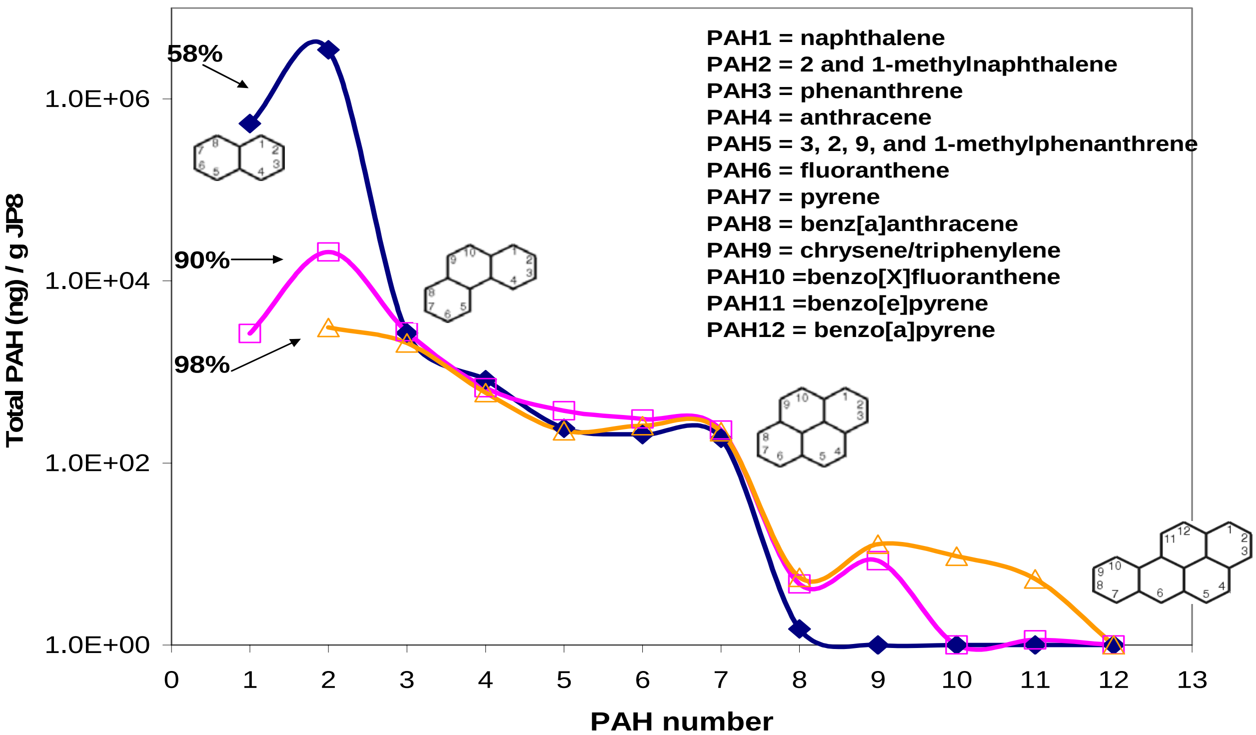


Figure 14. Concentration of PAH compounds in collected particulate matter from TF33 engine

4.3.1.3 Particle Number Density (PND)

The PND data for all tests are shown in Figure 15. PND values for the TF33 were generally between 20 X 10^6 and 50 X 10^6 particles per cm^3 with and without the additive. As expected, lower PND values were obtained at the lower power setting, which increased as the engine power was increased until the engine setting of 90%. At maximum power (98%), the particulate level decreased to the values of the 80% power, probably due to higher efficiency (improved soot combustion) at the higher power level. The first 40 tests were conducted with JP-8 and showed very good reproducibility (within 15%) at most power settings. Larger errors were observed at high power and when the engine operated on JP-8+100. Addition of the additive initially did not appear to impact the particulate emissions. After run number 70 (five hours of use of +100), there appeared to be reductions in PND at the 58, 70 and 80% power test conditions; however, a trend of increases in PND at the 90 and 98% conditions were also observed. The PND data, listed in Table 4-4, show that there was a reduction in PND for four of the five conditions; however, the calculated error (1-sigma) was higher than the observed reduction, thus, rendering the reductions statistically insignificant. Although at the end of the test program the trends showed reductions in PND for the lower power conditions, the lack of sufficient test runs precluded an acceptable statistical analysis with those data. Longer test times were needed to investigate the long-term effects of the additive on particulate emissions. However, as previously mentioned, longer tests are usually not practical and introduce

uncontrollable factors such as different fuels, atmospheric conditions and even engine wear and tear than can potentially impact emissions and cloud the real effects of the additive.

Particle emissions measurements at the two probe locations showed reasonably good agreement (within measurement uncertainty), which increases the confidence that a single point measurement may be representative of the particle loading for this type of engine.

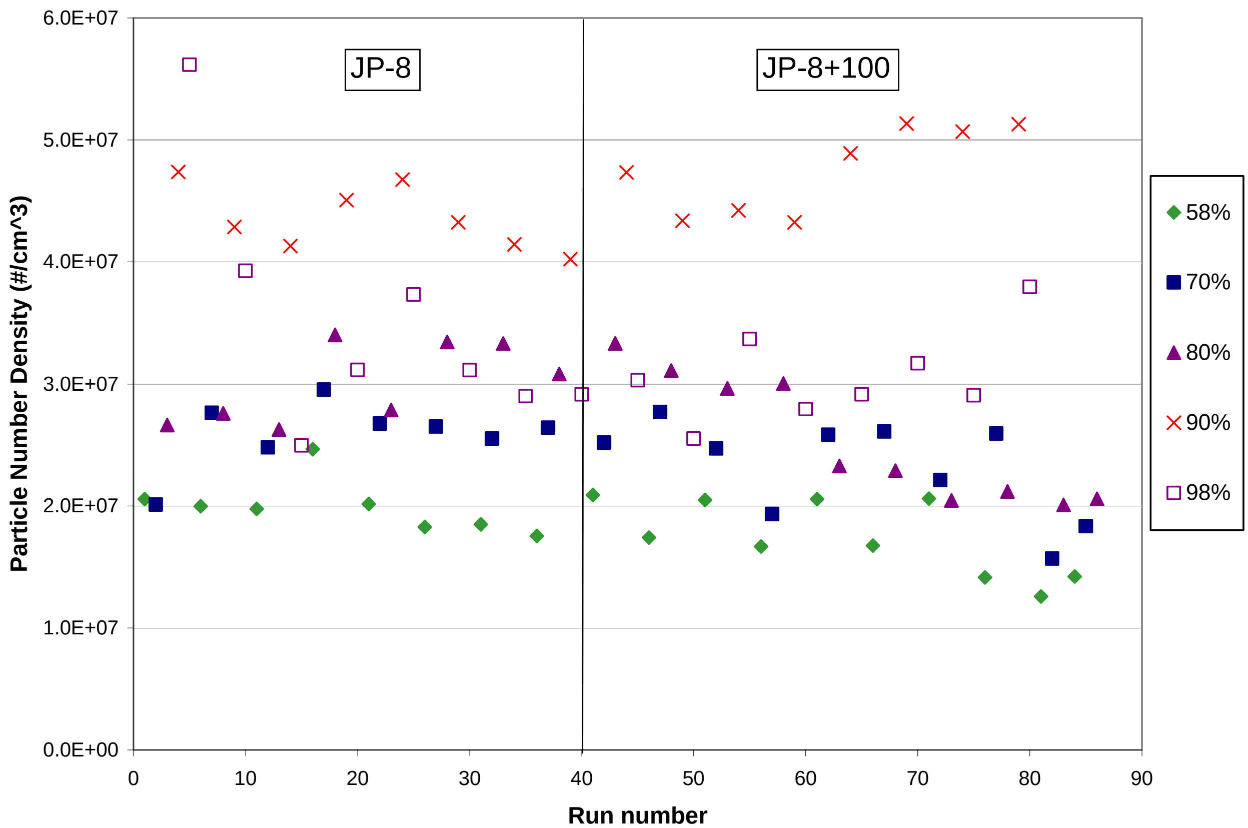


Figure 15. PND for TF33 engine at several Power Settings for JP-8 and JP-8+100

Table 4-4. Particle Number Density and 1σ error Data for TF33 Test I

	Engine Power Setting				
	58%	**70%**	**80%**	**90%**	**98%**
Average JP-8 (#/cm^3)	20×10^6	26×10^6	30×10^6	44×10^6	35×10^6
% error JP-8	11%	11%	11%	6%	28%
Average JP-8+100 (#/cm^3)	17×10^6	23×10^6	26×10^6	45×10^6	31×10^6
% error JP-8+100	18%	17%	20%	21%	12%
% change with additive	**-13%**	**-11%**	**-14%**	**2%**	**-12%**

4.3.1.4 Particle Size Distribution

A graph of particle mean diameters for the operating conditions tested is shown in Figure 16. Particle diameters were in the 60-115 nm range, and therefore significantly smaller than 2.5 µm (PM2.5). As expected, the particle mean size increased as a function of power setting. As shown, slight reductions in particle diameter with the additive were observed for all conditions tested. The largest reduction at 9% in diameter was observed for the idle condition (58%); however, considering the calculated error (variability) for each data set, the differences in particle mean diameter between the fuels are considered statistically insignificant.

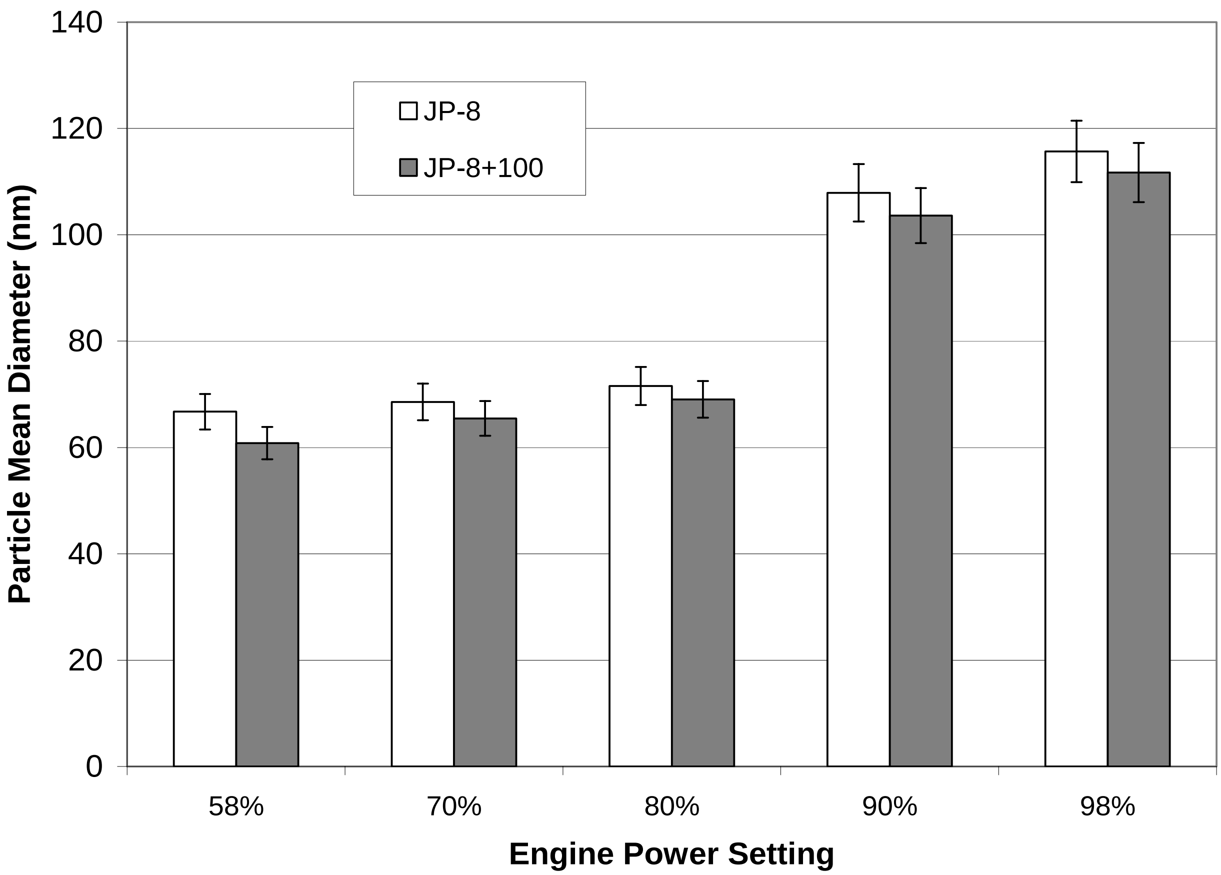


Figure 16. Effect of +100 additive on Particle Mean Diameter for TF33 engine tests I

4.3.1.5 Gaseous Emissions

Gaseous emissions measurements on the TF33 were performed by the Deposition Research Laboratory (DRL) to determine the environmental impact of the addition of +100 additive to JP-8. The gaseous species included: CO_2, CO, O_2, NO, NO_2, and CH_4. The higher power conditions yielded higher NO_x and lower CO emission indices, as anticipated. No change was observed for CO_2 and CH_4 (measure of THC) with the additive. Comparisons of the NO_x and CO gaseous emission indices for both fuels are shown in Table 4-5 for cases 58% and 90% engine power. As shown, the differences in NO_x and CO emissions between the fuels were

statistically insignificant. These results agreed very well with gaseous emissions measurements made by NIST.

Table 4-5 Comparison of NO_x and CO Emissions for JP-8 & JP-8+100 on the TF33 Test I

Engine Power %	Fuel	NO_x (g/kg fuel)	CO (g/kg fuel)
58%	JP-8	3.6±0.3	78.7±3.7
	JP-8+100	2.9±0.4	79.9±2.1
90%	JP-8	5.0±0.1	6.1±3.7
	JP-8+100	5.6±0.4	6.2±2.1

4.3.1.6 Summary

Gaseous and particulate emissions measurements were performed on a TF33 engine operated with JP-8 and JP-8+100 at test cell at Barksdale AFB. Results show no measurable impacts on gaseous emissions or on PAH content on the particles with the additive. Particulate emissions results show the potential of reductions with the additive especially after its prolonged use; however, additional data were needed to make a better assessment.

4.3.2 T-43 Aircraft at Randolph Air Force Base

4.3.2.1 Description and Objective

The effects of the +100 additive on the particulate and gaseous emissions of two T-43 aircraft each equipped with two P&W JT8D-9A engines were evaluated. A total of 165 tests runs were conducted in this test program. The test matrix is shown in Table 4-6 and the test setup in Figure 17. After the initial tests with JP-8, both aircraft were fueled with JP-8+100 for the remainder of the study. Both engines of Aircraft #1 were tested daily for three consecutive days after completion of the flight training mission (four hours). The emissions of Aircraft #2 were sampled when operating with baseline fuel, when first fueled with +100 and then after the last training mission using +100 (three days later). Eventually, each engine accumulated nearly 20 hours of operation on JP-8+100. Due to concerns by the T-43 SPO of potential aircraft fuel tank cleanup with the +100 additive and eventual fuel filter clogging, the aircraft and APU fuel filters were changed after the first JP-8+100 tests and after every 8-10 hours of operation with the additive. Inspection of the filters showed no debris or evidence of fuel tank cleanup due to the additive. Total engine run time (engine data summary), last overhaul cycle, and total run times on JP-8 and JP-8+100 are shown in Tables 4-7 and 4-8. Test data suggest that there is a trend of increased particulate emissions as a function of engine run time for most cases; however, a similar comparison using “hot section” run time (time since last hot section maintenance) shows no clear trend. Fuel analysis, emissions data and effects of the +100 additive on gaseous and particulate emissions on the JT8D-9A engines are discussed below.

Table 4-6. Test Matrix for T-43 Tests (four engines) at Randolph AFB

Test Pt	A/C	Eng	Fuel	Condition
1	1	1	JP8	Idle
2	1	1	JP8	Approach
3	1	1	JP8	Cruise
4	1	1	JP8	Climb
5	1	1	JP8	Hi Power
6	1	1	JP8	Idle
7	1	1	JP8	Approach
8	1	1	JP8	Cruise
9	1	1	JP8	Climb
10	1	1	JP8	Hi Power
11	1	1	JP8	Idle
12	1	1	JP8	Approach
13	1	1	JP8	Cruise
14	1	1	JP8	Climb
15	1	1	JP8	Hi Power
16	1	1	JP8	Idle
17	1	1	JP8	Approach
18	1	1	JP8	Cruise
19	1	1	JP8	Climb
20	1	1	JP8	Hi Power
Move Samp. Probe to Other Eng				
21	1	2	JP8	Idle
22	1	2	JP8	Approach
23	1	2	JP8	Cruise
24	1	2	JP8	Climb
25	1	2	JP8	Hi Power
26	1	2	JP8	Idle
27	1	2	JP8	Approach
28	1	2	JP8	Cruise
29	1	2	JP8	Climb
30	1	2	JP8	Hi Power
31	1	2	JP8	Idle
32	1	2	JP8	Approach
33	1	2	JP8	Cruise
34	1	2	JP8	Climb
35	1	2	JP8	Hi Power
36	1	2	JP8	Idle
37	1	2	JP8	Approach
38	1	2	JP8	Cruise
39	1	2	JP8	Climb
40	1	2	JP8	Hi Power
41	1	1	JP8+100	Idle
42	1	1	JP8+100	Approach
43	1	1	JP8+100	Cruise
44	1	1	JP8+100	Climb
45	1	1	JP8+100	Hi Power
46	1	1	JP8+100	Idle
47	1	1	JP8+100	Approach
48	1	1	JP8+100	Cruise
49	1	1	JP8+100	Climb
50	1	1	JP8+100	Hi Power
51	1	1	JP8+100	Idle
52	1	1	JP8+100	Approach
53	1	1	JP8+100	Cruise
54	1	1	JP8+100	Climb
55	1	1	JP8+100	Hi Power
56	1	1	JP8+100	Idle
57	1	1	JP8+100	Approach
58	1	1	JP8+100	Cruise
59	1	1	JP8+100	Climb
60	1	1	JP8+100	Hi Power
Move Samp. Probe to Other Eng				
61	1	2	JP8+100	Idle
62	1	2	JP8+100	Approach
63	1	2	JP8+100	Cruise
64	1	2	JP8+100	Climb
65	1	2	JP8+100	Hi Power
66	1	2	JP8+100	Idle
67	1	2	JP8+100	Approach
68	1	2	JP8+100	Cruise
69	1	2	JP8+100	Climb
70	1	2	JP8+100	Hi Power
71	2	1	JP8	Idle
72	2	1	JP8	Approach
73	2	1	JP8	Cruise
74	2	1	JP8	Climb
75	2	1	JP8	Hi Power
76	2	1	JP8	Idle
77	2	1	JP8	Approach
78	2	1	JP8	Cruise
79	2	1	JP8	Climb
80	2	1	JP8	Hi Power
81	2	1	JP8	Idle
82	2	1	JP8	Approach
83	2	1	JP8	Cruise
84	2	1	JP8	Climb
85	2	1	JP8	Hi Power
Move Samp. Probe to Other Eng				
86	2	2	JP8	Idle
87	2	2	JP8	Approach
88	2	2	JP8	Cruise
89	2	2	JP8	Climb
90	2	2	JP8	Hi Power
91	2	2	JP8	Idle
92	2	2	JP8	Approach
93	2	2	JP8	Cruise
94	2	2	JP8	Climb
95	2	2	JP8	Hi Power
96	2	2	JP8	Idle
97	2	2	JP8	Approach
98	2	2	JP8	Cruise
99	2	2	JP8	Climb
100	2	2	JP8	Hi Power
101	2	1	JP8+100	Idle
102	2	1	JP8+100	Approach
103	2	1	JP8+100	Cruise
104	2	1	JP8+100	Climb
105	2	1	JP8+100	Hi Power
106	2	1	JP8+100	Idle
107	2	1	JP8+100	Approach
108	2	1	JP8+100	Cruise
109	2	1	JP8+100	Climb
110	2	1	JP8+100	Hi Power
111	2	1	JP8+100	Idle
112	2	1	JP8+100	Approach
113	2	1	JP8+100	Cruise
114	2	1	JP8+100	Climb
115	2	1	JP8+100	Hi Power
Move Samp. Probe to Other Eng				
116	2	2	JP8+100	Idle
117	2	2	JP8+100	Approach
118	2	2	JP8+100	Cruise
119	2	2	JP8+100	Climb
120	2	2	JP8+100	Hi Power
121	2	2	JP8+100	Idle
122	2	2	JP8+100	Approach
123	2	2	JP8+100	Cruise
124	2	2	JP8+100	Climb
125	2	2	JP8+100	Hi Power
126	1	1	JP8+100	Idle
127	1	1	JP8+100	Approach
128	1	1	JP8+100	Cruise
129	1	1	JP8+100	Climb
130	1	1	JP8+100	Hi Power
131	1	1	JP8+100	Idle
132	1	1	JP8+100	Approach
133	1	1	JP8+100	Cruise
134	1	1	JP8+100	Climb
135	1	1	JP8+100	Hi Power
136	1	1	JP8+100	Idle
137	1	1	JP8+100	Approach
138	1	1	JP8+100	Cruise
139	1	1	JP8+100	Climb
140	1	1	JP8+100	Hi Power
141	1	1	JP8+100	Idle
142	1	1	JP8+100	Approach
143	1	1	JP8+100	Cruise
144	1	1	JP8+100	Climb
145	1	1	JP8+100	Hi Power
Move Samp. Probe to Other Eng				
146	1	2	JP8+100	Idle
147	1	2	JP8+100	Approach
148	1	2	JP8+100	Cruise
149	1	2	JP8+100	Climb
150	1	2	JP8+100	Hi Power
151	1	2	JP8+100	Idle
152	1	2	JP8+100	Approach
153	1	2	JP8+100	Cruise
154	1	2	JP8+100	Climb
155	1	2	JP8+100	Hi Power
156	1	2	JP8+100	Idle
157	1	2	JP8+100	Approach
158	1	2	JP8+100	Cruise
159	1	2	JP8+100	Climb
160	1	2	JP8+100	Hi Power
161	1	2	JP8+100	Idle
162	1	2	JP8+100	Approach
163	1	2	JP8+100	Cruise
164	1	2	JP8+100	Climb
165	1	2	JP8+100	Hi Power

Figure 17. Engine emissions measurements from T-43 aircraft at Randolph Air Force Base

Table 4-7 T-43 Engine Data Summary

Aircraft #1 #1 Engine LH s/n PW00674**613** Current hours 6134.4 Hot Section 7/99 @ 4561 Overhauled 1/90 @ 16578 Total Time #2 Engine RH s/n PW00674**607** Current hours 7000.3 Hot Section 12/98 @ 5246 Overhauled 8/88 @ 12035 Total Time
Aircraft #2 #1 Engine LH s/n PW00674**608** Current hours 5117.7 Hot Section 2/00 @ 4308 Overhauled 12/91 @ 9975 Total Time #2 Engine RH s/n PW00674**636** Current hours 6615.4 Hot Section 5/99 @ 5365 Overhauled 3/89 @ 12071 Total Time

Table 4-8 Run time (hrs) on JP-8+100

Date	Test/Fly	Aircraft #1	Aircraft #2
Nov 17, 2002	Test	2.1 Baseline	-
Nov 18, 2002	Test Baseline	-	2.2
Nov 19, 2002	Fly Test	4.0 .2 (Probe Failure)	3.9
Nov 20, 2002	Fly Test	5.2 3.3	4.3 -
Nov 21, 2002	Fly Test	4.6 2.7	4.6 -
Nov 22, 2002	Test	-	2.7

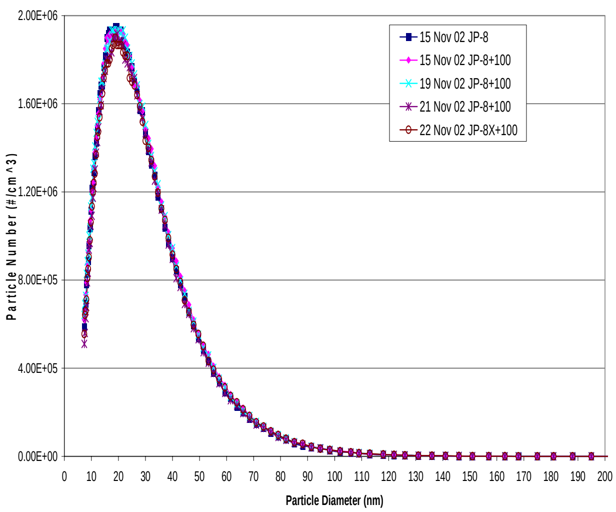
4.3.2.2 Fuel Analysis and Combustion Tests

ASTM JP-8 specification tests were performed on all fuels used in this study (see Table 4-9). The total sulfur content for all fuels was similar and significantly below the JP-8 specification values. The aromatic content, at 12.5-14% by volume, was similar for all fuels except for the sample on the 19 November in which the aromatic level was an atypical 19%.

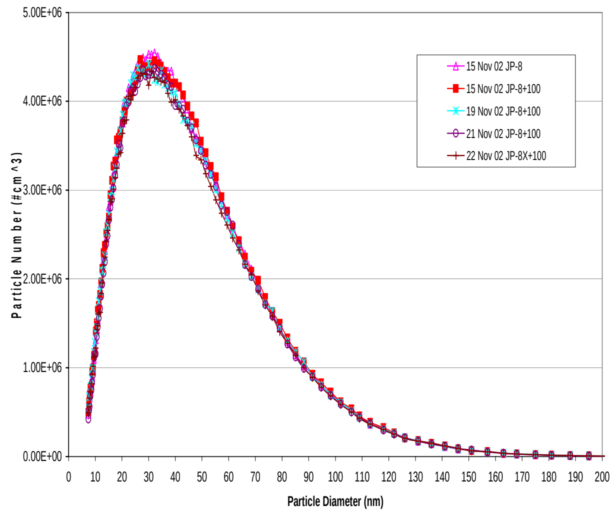
Table 4-9. ASTM JP-8 Specification Tests for fuels used at Randolph AFB in Nov. 2002 tests

ASTM Tests	Standard	JP-8 (15-18 Nov)	JP-8+100 (15-18 Nov)	JP-8+100 (19 Nov)	JP-8+100 (21 Nov)	JP-8+100 (22 Nov)
Total Acid Number, mg KOH/g (D3242)	Max 0.015	0.005	0.004	0.006	0.003	0.004
Aromatics, %vol (D1319)	Max 25.0	14.2	14.1	19.0	13.9	12.6
Total Sulfur, % mass (D4294)	Max 0.30	0.02	0.02	0.00	0.02	0.02
Distillation-Residue, % vol (D86)	Max 1.5	1.5	1.0	0.8	1.1	1.4
Distillation-EP, deg C (D86)	Max 300	238	247	235	233	237
Freezing Point, deg C (D5972)	Max -47	-51	-57	-54	-58	-59
Existent Gum, mg/100mL (D381)	Max 7.0	0.0	0.2	1.0	0.0	3.0
Viscosity @ -20deg C, cSt (D445)	Max 8.0	4.5	4.0	4.1	4.6	5.1
FSII (DiEGME), % vol (D5006)	0.10-0.15	0.11	0.15	0.13	0.11	0.11
Conductivity, pS/m (D2624)	150-600	120	71	424	645	565

Combustion tests with the fuels used in the T-43 emissions tests were performed in an in-house T63 engine. For these tests, the engine was operated at idle and cruise power conditions. The particle size distributions for these tests are shown in Figure 18. At the idle condition the size distribution curves were almost identical for all fuels tested with the peak diameter near 20 nm. At cruise, the size distribution curves were also similar with slightly lower particle numbers for the last fuel used (22 Nov 02) and with a peak diameter near 32 nm. Slightly lower total particle concentrations (PND) for the 22 Nov 02 fuel can be observed, however, the differences in particle loading between the various field fuels were within 5% of the measurement, which is statistically insignificant. The higher aromatic fuel (Nov 19 02) did not appear to impact the size distribution or total particle count on the T63. This was unexpected considering that aromatics are well-known soot precursors that have been shown to increase particle concentrations and size (Corporan et al, 2004).



(a) Idle



(b) Cruise

Figure 18. Particle Size Distribution for T63 Engine with fuels used during T-43 tests

4.3.2.3 Impact of Sample Probe Position

The particulate emissions were sampled from three (3) sample probes placed along the lower half of the vertical centerline of the engines. Each probe was routed to a dedicated particle counter (CNC). Particle probe dilution ratios were determined by comparing the undiluted and diluted CO_2 samples in the particulate sample. The dilution ratios were found to be in the range of 8:1 to 10:1 for all engine conditions. The probe setup is shown in Figure 19. A system of shutoff valves was used to switch the probes to different counters to determine if there was any probe position or instrumentation bias on the particulate measurement. All combinations of the three probe positions and three instrumentation packages were tested to address potential discrepancies between the instrumentation packages and uniformity of the PM exhaust. The test results, shown in Figure 20, indicate little bias as a function of probe position at idle and high power settings suggesting that the particulate emissions were quite uniform in the range of positions tested. These results are encouraging since they increase the confidence that a single point measurement is fairly representative of the engine exhaust

emissions. Significant discrepancies were only observed with one of the counters (CNC 3), which showed large uncertainties particularly with probes 2 and 3.

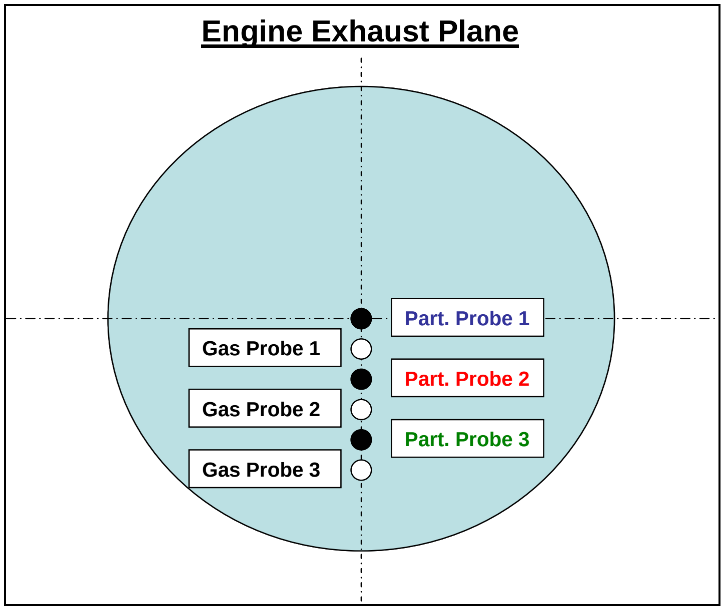


Figure 19. Sampling Probes Setup in T-43 Tests

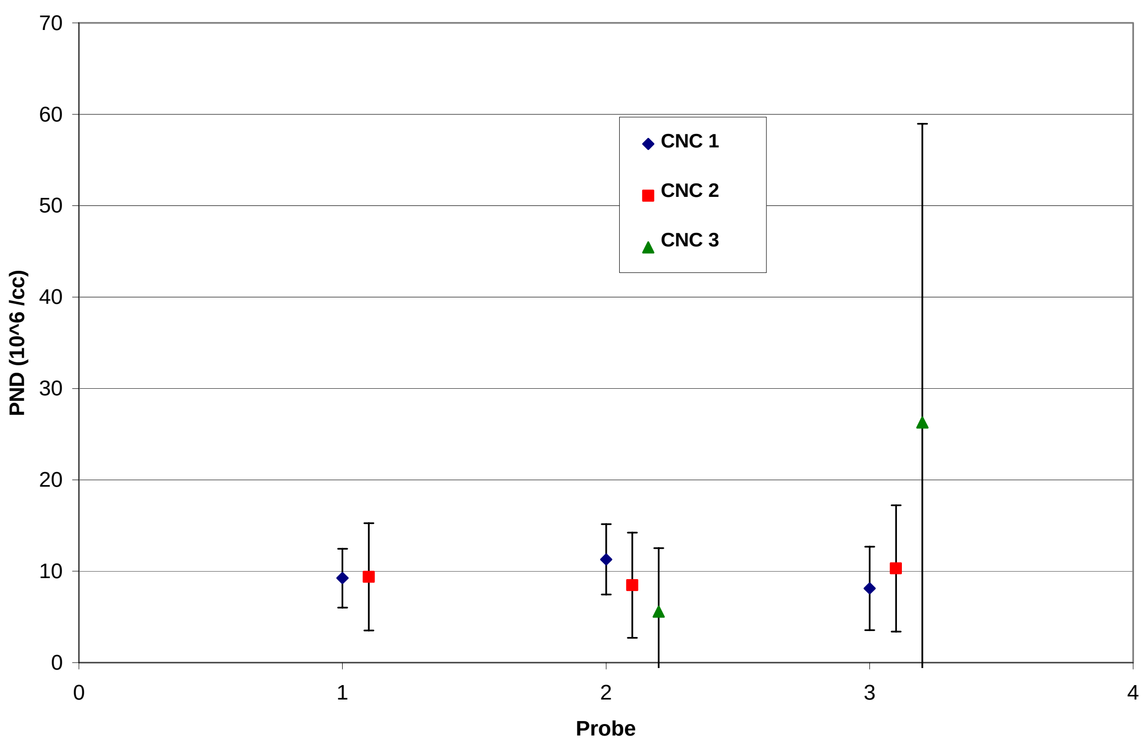


Figure 20. Particulate Emissions Profile JT8D-9A Engine on T-43 at High Power

4.3.2.4 Particle Number Density

Average PND data for all four engines as a function of power setting and run time are shown in Figure 21 and Figure 22. Precision (repeatability) errors for the PND measurements for most tests were 10-20%. Variations in PM emissions between the same engine setting during the different cycles could be partly the result of not obtaining exactly the same setting for that condition. The engine power was controlled by adjusting the engine pressure ratio (EPR) as displayed on the control console; therefore, matching engine power settings between cycles was highly dependent on the reliability or precision of the aircraft instrumentation. As shown, all four engines produced similar PND values and trends as a function of power setting. Values of 2.0-3.0 x 10^6 particles per cm^3 were observed for the idle condition, while 4.0-8.0 x 10^6 particles per cm^3 were common for the mid-power levels. At the higher power setting, the values decreased to 3.0-5.0 x 10^6 particles per cm^3 for most conditions. Comparison of particulate emissions between the engines operating with JP-8+100 and the baseline fuel showed no consistent trend. For engine #613, an average reduction of approximately 40% in PND with the +100 additive was observed for all power conditions. Also, significant variation in the PND was observed as a function of time but with no clear trend. It is noteworthy that engine #613 is the oldest (highest run times) of the four engines tested, which suggest that the +100 may have a positive impact on emissions in high-use engines. Further work is needed to support this hypothesis. No clear trend of +100 additive effects as a function of engine use time was observed for the other engines. For engines 608 and 636 there also appears to be a slight reduction in PND for the engines operating for 20 hrs with the additive; however, there was also an increase in PND for engines 607 and 636 after a 1.5 hour JP-8+100 use. The latter could be the result of increased particulate emissions as the engine was cleaned with the additive; however, these results were inconsistent with all engines and power settings. It is important to note that a change in PND does not necessarily translate into the same magnitude change in mass. Direct particulate mass measurements were not made in these studies.

4.3.2.5 Particle Mean Diameter

The particle size distribution was determined using a differential mobility analyzer (DMA) in combination with a condensation nuclei counter (CNC). Listed in Table 4-10 are the averages of mean particle diameters of the particulate emissions for the conditions considered. The particle diameter is an important parameter since its relation to mass is to the third power. Particle diameters for the four JT8D-9A engines varied from 50 to 83 nm, with the smallest particles at idle and the largest at one of the three highest power settings. The small mean particle diameter at idle may be partly the result of large concentrations of volatile particles resulting from uncombusted or partially combusted jet fuel. Separation of volatile and non-volatile particles was not performed in this study. As shown, for engine #613 reductions in the particle size were observed with the additive for all conditions except idle. For two of the four engines (607 & 608), there were increases in particle size with the additive ranging from 1.6 to 25%, with the largest increases occurring at the low power setting (idle). Negligible changes in particle size were observed for engine #636. From these results it is clear that the impacts of the +100 additive on engine particulate emissions cannot be generalized since they differ significantly depending on engine and test conditions.

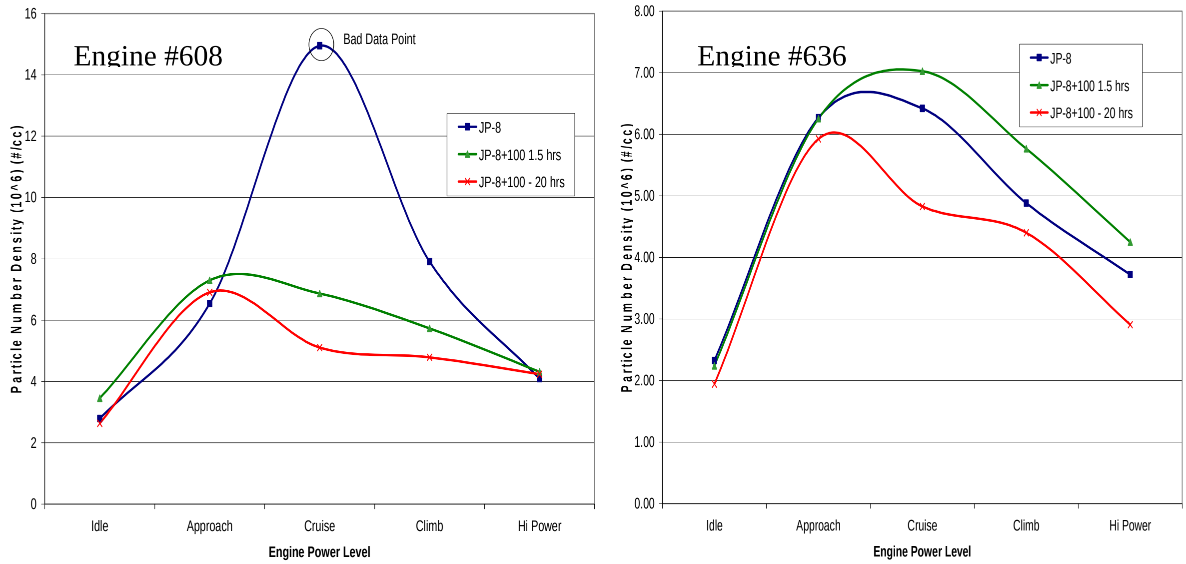


Figure 21. PND as a function of Power Setting for T-43 Engines 608 and 636

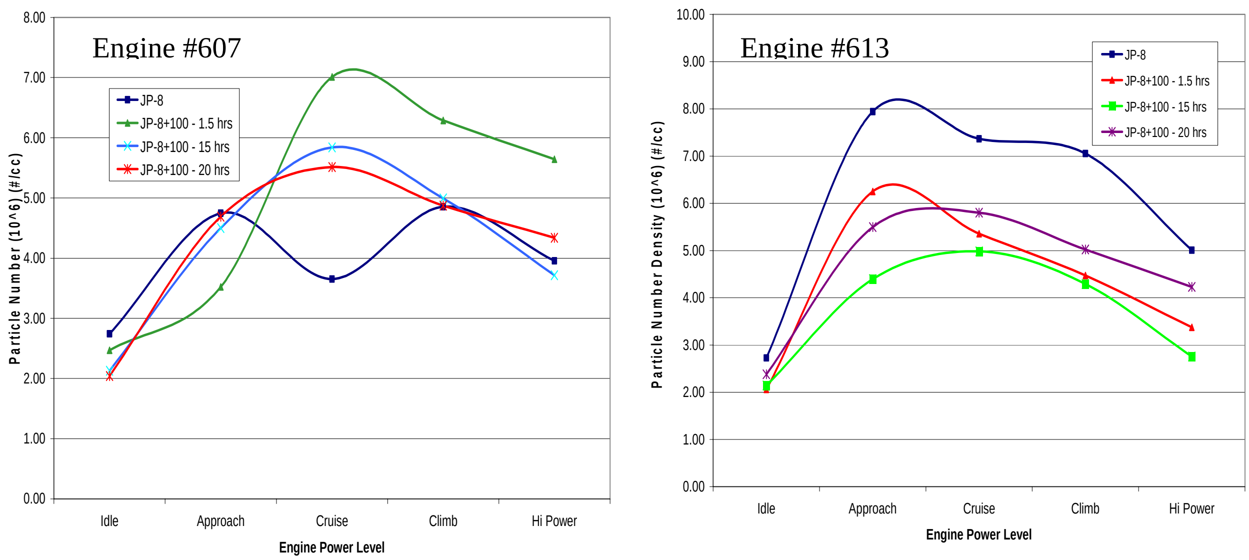


Figure 22. PND as a function of Power Setting for T43 Engines 607 and 613

Table 4-10. Particle Mean Diameter for T-43 engines using JP-8 and JP-8+100

Engine 613			
	Particle Mean Diameter (nm)		
Power level	**JP-8**	**JP-8+100 (20 hrs)**	**% change**
Idle	53.3	55.8	4.6%
Approach	68.2	62.3	-8.7%
Cruise	82.0	75.0	-8.5%
Climb	78.0	74.3	-4.8%
Hi-Power	83.0	72.8	-12.3%

Engine 636			
	Particle Mean Diameter (nm)		
Power level	**JP-8**	**JP-8+100 (20 hrs)**	**% change**
Idle	52.0	52.0	0.0%
Approach	70.0	71.0	1.4%
Cruise	75.0	74.3	-0.9%
Climb	78.0	78.3	0.4%
Hi-Power	83.0	76.7	-7.6%

Engine 608			
	Particle Mean Diameter (nm)		
Power level	**JP-8**	**JP-8+100 (20 hrs)**	**% change**
Idle	50.0	62.8	25.5%
Approach	71.0	74.7	5.2%
Cruise	74.0	80.3	8.6%
Climb	81.0	80.0	-1.2%
Hi-Power	78.0	80.0	2.6%

Engine 607			
	Particle Mean Diameter (nm)		
Power level	**JP-8**	**JP-8+100 (20 hrs)**	**% change**
Idle	47.0	58.3	24.1%
Approach	62.0	63.0	1.6%
Cruise	71.0	73.0	2.8%
Climb	73.0	74.7	2.3%
Hi-Power	66.0	78.0	18.2%

4.3.2.6 Gaseous Emissions

Gaseous emissions were extracted from the JT8D-9A engines via three undiluted gas sampling probes positioned vertically inline near and below the centerline of the engine. The gaseous streams from the particulate probes were sampled in a separate manifold to measure CO_2, O_2, NO_2, NO, and CO to determine their emission indices. Average emission indices for NO_x and CO for two engines at the five power settings are shown in Table 4-11.

Table 4-11. Emission Indices (g/kg-fuel) of NO_x and CO emissions from T-43 engines

Engine 607	**JP-8**		**JP-8+100**		**% change relative to JP-8**	
	NOx	**CO**	**NOx**	**CO**	**NOx**	**CO**
Idle	3.4	20.5	2.7	15.9	-21%	-22%
Approach	6.4	6.6	6.5	3.8	2%	-43%
Cruise	9.6	1.4	12.7	0.5	32%	-64%
Climb	10.9		14.1		29%	
High Power	17.2		17.0		-1%	

Engine 613	**JP-8**		**JP-8+100**		**% change relative to JP-8**	
	NOx	**CO**	**NOx**	**CO**	**NOx**	**CO**
Idle	1.9	16.0	4.5	18.7	134%	17%
Approach	5.9	3.8	8.2	4.3	40%	12%
Cruise	11.4	0.4	13.9	1.8	22%	327%
Climb	13.9		15.5		11%	
High Power	17.0		18.7		10%	

As expected, as the power level increased the NO_x emissions increased and CO emissions decreased. At the two highest power settings, the CO emissions were below the sensitivity limits of the instrument; therefore, data were not collected. The effects of the +100 additive on these emissions factors were inconsistent between the engines and power conditions. For

engine #607, CO emissions decreased with the additive, however, NO_x emissions increased significantly for two of the five power settings. For engine #613, both NO_x and CO emissions increased. Statistical analysis shows errors up to 46% for the NO_x and CO measurements at the low end of the sensor range (e.g., NO_x at idle, CO at approach and cruise), therefore rendering the data statistically insignificant. These gaseous emissions results were based on only four runs per condition, and therefore, more test runs are needed to produce enough data for a thorough statistical analysis and improved assessment of the effects of the additive on gaseous emissions. Results show no clear correlation between emissions and engine age or last maintenance cycle.

4.3.2.7 Summary

Particulate and gaseous emissions measurements were performed on four JT8D-9A engines installed on two T-43 aircraft at Randolph Air Force Base. The engines were initially run on JP-8 and then converted to JP-8+100 for the remaining of the study. The impact of the additive on emissions was inconsistent as it was dependent on engine and power condition. PND reductions up to 40% were observed for one of the engines using the +100 additive. Minor reductions were observed with the other engines; however, most were statistically insignificant. An increase in particulate emissions with the additive was observed for one of the engines (#607) presumably as the engine turbine and combustor were cleaned; however, this hypothesis does not hold true for the rest of the engines and power settings.

4.3.3 TF33 Tests II at Barksdale Air Force Base

4.3.3.1 Description and Objective

Tests were conducted on a TF33 engine at Barksdale AFB La. The test plan was similar to the first +100 evaluation in this engine type; however, more efficient (lower loss) probes and multiple counters were used to improve data quality and to simultaneously sample from two locations without relocating the probe stand. In addition to the gaseous and particulate measurements, the engine was inspected with a borescope and pictures taken before and after several hours of testing with and without the additive to assess engine cleanliness. A total of 165 test runs, consisting of 35 cycles of five test conditions per cycle, were conducted. The test matrix is shown in Table 4-12. The first 40 test runs, approximately 4.5 hours of actual engine run time, were performed with JP-8; the remainder of the tests (approximately 16 hours), were completed with JP-8+100. The fuel was treated with the additive by pouring it in the 2000 gallon facility tank and manually mixing at approximately 256 mg additive per liter fuel.

4.3.3.2 Particle Number Density

The complete data set of the engine PND for different conditions as a function of time (run number) and test day is shown in Figure 23. The engine was operated with JP-8 for the first 40 test runs (Monday tests) and subsequent tests with JP-8+100. As shown, there was a significant increase in PND with the continuous use of JP-8 (from run 1-40). This sharp increase in particle loading with JP-8 is not well understood, and it could be due to a combination of factors including: progressive fouling of fuel nozzles, slight differences in engine operating conditions, changes or uncertainties in dilution flows or unknown

Table 4-12. Test matrix TF33 tests II at Barksdale Air Force Base

Run No.	Pwr	Cycle	Fuel	Run No.	Pwr	Cycle	Fuel
1	58	1	JP-8	86	58	18	JP-8+100
2	70	1	JP-8	87	70	18	JP-8+100
3	80	1	JP-8	88	80	18	JP-8+100
4	90	1	JP-8	89	90	18	JP-8+100
5	98	1	JP-8	90	98	18	JP-8+100
6	58	2	JP-8	91	58	19	JP-8+100
7	70	2	JP-8	92	70	19	JP-8+100
8	80	2	JP-8	93	80	19	JP-8+100
9	90	2	JP-8	94	90	19	JP-8+100
10	98	2	JP-8	95	98	19	JP-8+100
11	58	3	JP-8	96	58	20	JP-8+100
12	70	3	JP-8	97	70	20	JP-8+100
13	80	3	JP-8	98	80	20	JP-8+100
14	90	3	JP-8	99	90	20	JP-8+100
15	98	3	JP-8	100	98	20	JP-8+100
16	58	4	JP-8	101	58	21	JP-8+100
17	70	4	JP-8	102	70	21	JP-8+100
18	80	4	JP-8	103	80	21	JP-8+100
19	90	4	JP-8	104	90	21	JP-8+100
20	98	4	JP-8	105	98	21	JP-8+100
21	58	5	JP-8	106	58	22	JP-8+100
22	70	5	JP-8	107	70	22	JP-8+100
23	80	5	JP-8	108	80	22	JP-8+100
24	90	5	JP-8	109	90	22	JP-8+100
25	98	5	JP-8	110	98	22	JP-8+100
26	58	6	JP-8	111	58	23	JP-8+100
27	70	6	JP-8	112	70	23	JP-8+100
28	80	6	JP-8	113	80	23	JP-8+100
29	90	6	JP-8	114	90	23	JP-8+100
30	98	6	JP-8	115	98	23	JP-8+100
31	58	7	JP-8	116	58	24	JP-8+100
32	70	7	JP-8	117	70	24	JP-8+100
33	80	7	JP-8	118	80	24	JP-8+100
34	90	7	JP-8	119	90	24	JP-8+100
35	98	7	JP-8	120	98	24	JP-8+100
36	58	8	JP-8	121	58	25	JP-8+100
37	70	8	JP-8	122	70	25	JP-8+100
38	80	8	JP-8	123	80	25	JP-8+100
39	90	8	JP-8	124	90	25	JP-8+100
40	98	8	JP-8	125	98	25	JP-8+100
41	58	9	JP-8+100	126	58	26	JP-8+100
42	70	9	JP-8+100	127	70	26	JP-8+100
43	80	9	JP-8+100	128	80	26	JP-8+100
44	90	9	JP-8+100	129	90	26	JP-8+100
45	98	9	JP-8+100	130	98	26	JP-8+100
46	58	10	JP-8+100	131	58	27	JP-8+100
47	70	10	JP-8+100	132	70	27	JP-8+100
48	80	10	JP-8+100	133	80	27	JP-8+100
49	90	10	JP-8+100	134	90	27	JP-8+100
50	98	10	JP-8+100	135	98	27	JP-8+100
51	58	11	JP-8+100	136	58	28	JP-8+100
52	70	11	JP-8+100	137	70	28	JP-8+100
53	80	11	JP-8+100	138	80	28	JP-8+100
54	90	11	JP-8+100	139	90	28	JP-8+100
55	98	11	JP-8+100	140	98	28	JP-8+100
56	58	12	JP-8+100	141	58	29	JP-8+100
57	70	12	JP-8+100	142	70	29	JP-8+100
58	80	12	JP-8+100	143	80	29	JP-8+100
59	90	12	JP-8+100	144	90	29	JP-8+100
60	98	12	JP-8+100	145	98	29	JP-8+100
61	58	13	JP-8+100	146	58	30	JP-8+100
62	70	13	JP-8+100	147	70	30	JP-8+100
63	80	13	JP-8+100	148	80	30	JP-8+100
64	90	13	JP-8+100	149	90	30	JP-8+100
65	98	13	JP-8+100	150	98	30	JP-8+100
66	58	14	JP-8+100	151	58	31	JP-8+100
67	70	14	JP-8+100	152	70	31	JP-8+100
68	80	14	JP-8+100	153	80	31	JP-8+100
69	90	14	JP-8+100	154	90	31	JP-8+100
70	98	14	JP-8+100	155	98	31	JP-8+100
71	58	15	JP-8+100	156	58	32	JP-8+100
72	70	15	JP-8+100	157	70	32	JP-8+100
73	80	15	JP-8+100	158	80	32	JP-8+100
74	90	15	JP-8+100	159	90	32	JP-8+100
75	98	15	JP-8+100	160	98	32	JP-8+100
76	58	16	JP-8+100	161	58	33	JP-8+100
77	70	16	JP-8+100	162	70	33	JP-8+100
78	80	16	JP-8+100	163	80	33	JP-8+100
79	90	16	JP-8+100	164	90	33	JP-8+100
80	98	16	JP-8+100	165	98	33	JP-8+100
81	58	17	JP-8+100				
82	70	17	JP-8+100				
83	80	17	JP-8+100				

instrumentation artifacts. Addition of the +100 additive (run 41) appeared to have reduced the PND to the original JP-8 baseline levels. Subsequent use of JP-8+100 increased particulate emissions (runs 41-75), which then stabilized to values between 15.0 X 10^6 and 25.0 X 10^6 for all the conditions tested. Average particle concentrations for each test condition per day with their respective one standard deviation errors are shown in Table 4-13. The same data are plotted in Figure 24 with the average error bars displayed for each day. As shown, there is an apparent trend of particle concentration reduction on a daily basis for all conditions; however, the uncertainties in the emissions measurements were significant. The uncertainties were lower for the first five JP-8 measurements (JP-8 First five runs - each run representing at minimum of 300 data points), but were still relatively significant at an average of 27%.

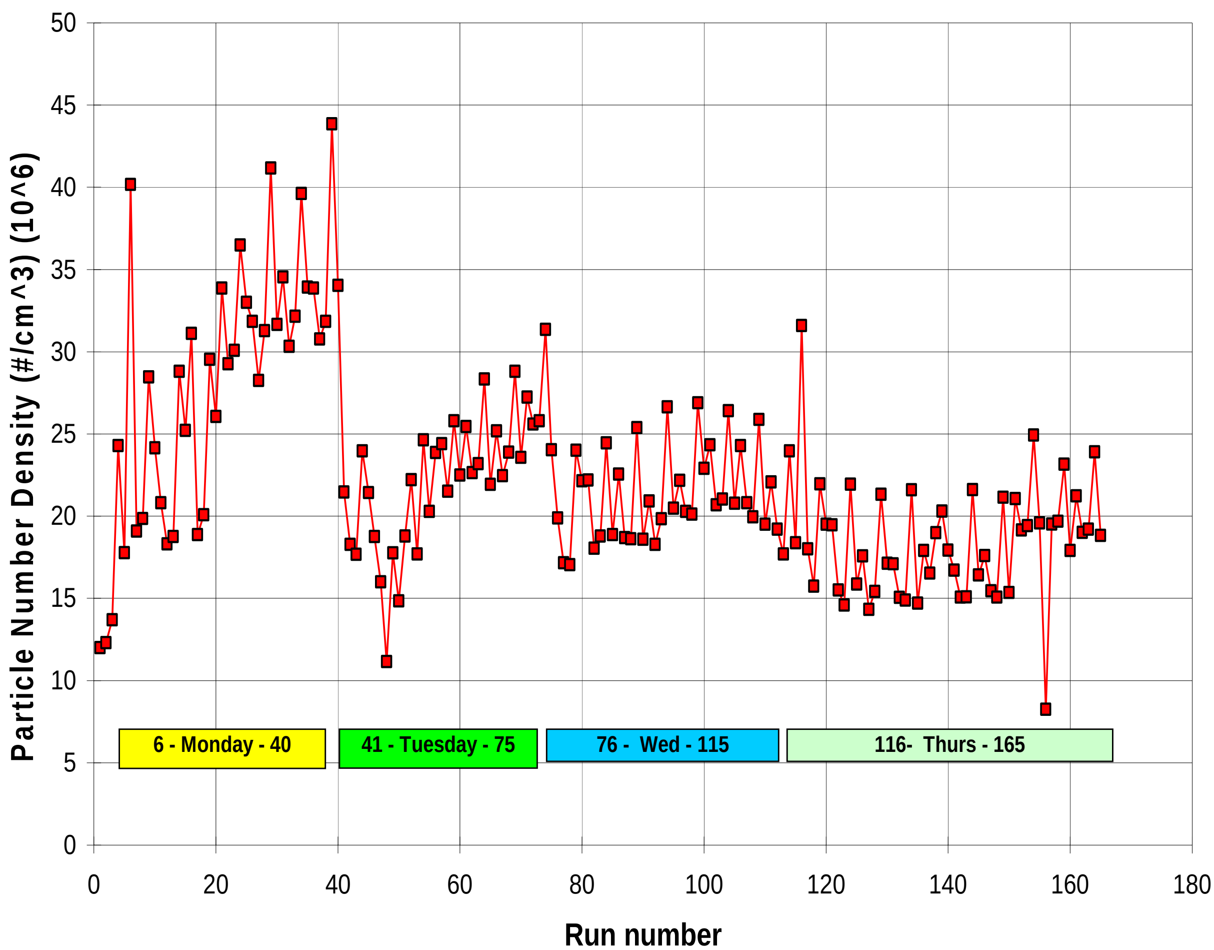


Figure 23. PND as a Function of Run Number for TF33 Test II

Table 4-13. PND (10^6) and Error Data for TF33 Test II

Test Day (Fuel)	Average PND (10^6) Error (1-sigma)	Engine Power Condition 58	70	80	90	98
Monday (JP-8 all)	Average	32.9	28.6	30.9	40.2	36.0
Monday (JP-8 all)	Error	38%	59%	64%	49%	66%
Monday (JP-8 First five runs)	Average	27.6	19.6	20.5	29.5	25.2
Monday (JP-8 First five runs)	Error	40%	31%	29%	15%	22%
Tuesday (JP-8+100)	Average	23.0	21.7	20.1	25.8	21.2
Tuesday (JP-8+100)	Error	15%	16%	25%	17%	15%
Wednesday (JP-8+100)	Average	22.3	19.1	19.1	25.5	20.6
Wednesday (JP-8+100)	Error	7%	7%	7%	5%	10%
Thursday (JP-8+100)	Average	18.6	16.8	16.8	22.2	17.3
Thursday (JP-8+100)	Error	10%	12%	13%	6%	10%

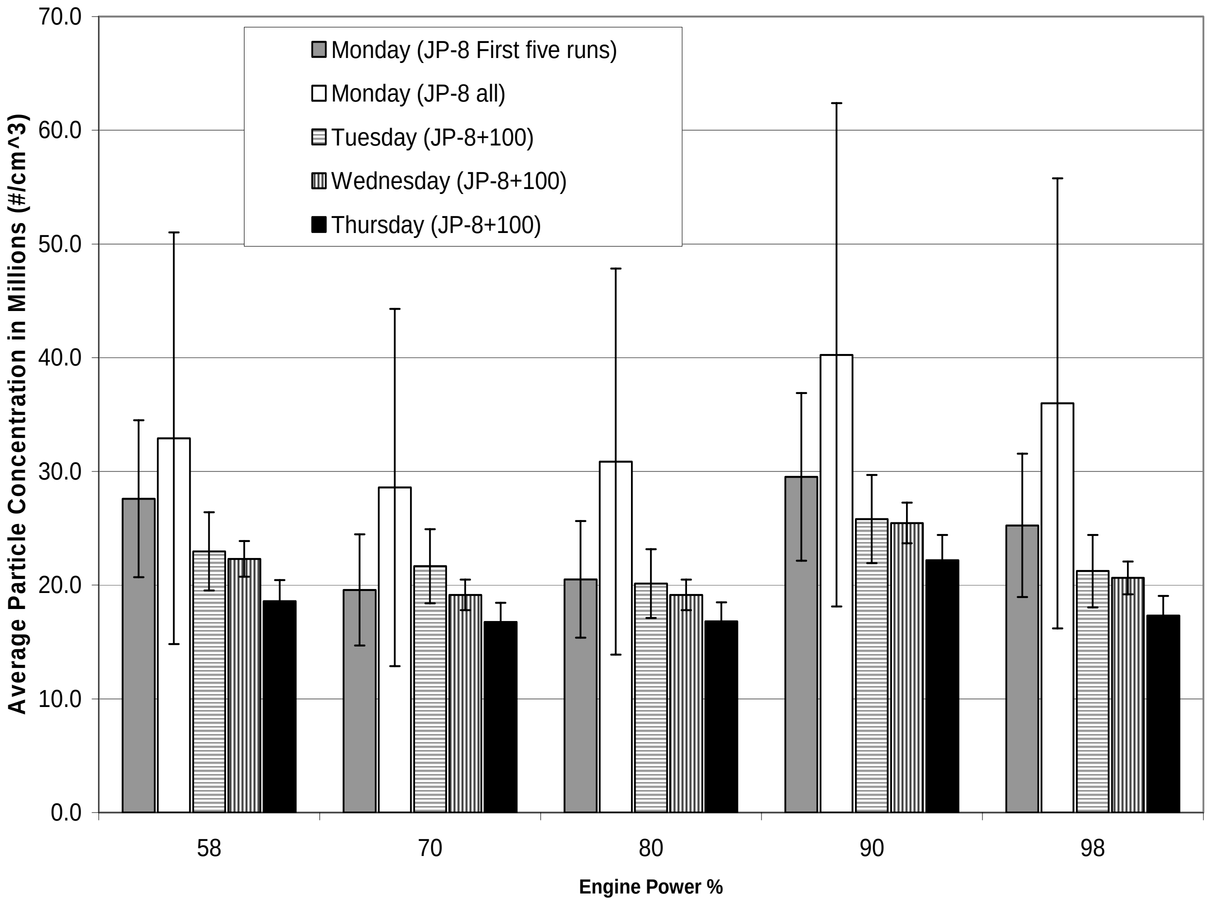


Figure 24. PND as a Function of Engine Power for TF33 Tests II

4.3.3.3 Particle Size Distribution and Mass

A comparison of particle mass based on TEOM measurements for the conditions tested is shown in Figure 25. The effects of the additive on particle mass were insignificant at the lowest three power settings. At full power, there appeared to be an increase in particle mass with the additive, however, a t-test analysis revealed that it was also statistically insignificant. The only power setting that showed statistically significant reductions between particle mass sample averages was at the 90% setting. Approximately 30% reduction in particle mass emissions was observed at the 90% condition. Particle mass emissions based on size distribution (from DMA measurements) and particle number are shown in Figure 26. This computed mass assumes that particles are spherical and that they all have the same density (1.2 g/cc). Caution should be exercised when reaching conclusions based on these results since the assumptions of geometry and particle density could lead to significant error and data misinterpretation. Statistical analysis (t-test) for these mass computed results show reductions between 22-40% in mass emissions for all test conditions. The largest improvements were observed at the higher power settings. The only DMA-based mass result that is consistent with the reductions measured with the TEOM is at the 90% condition, which showed a reduction of 40%. Uncertainties in both measurements and the assumptions used in the computed mass can explain the discrepancies between the TEOM mass measurements and the DMA-based calculated mass.

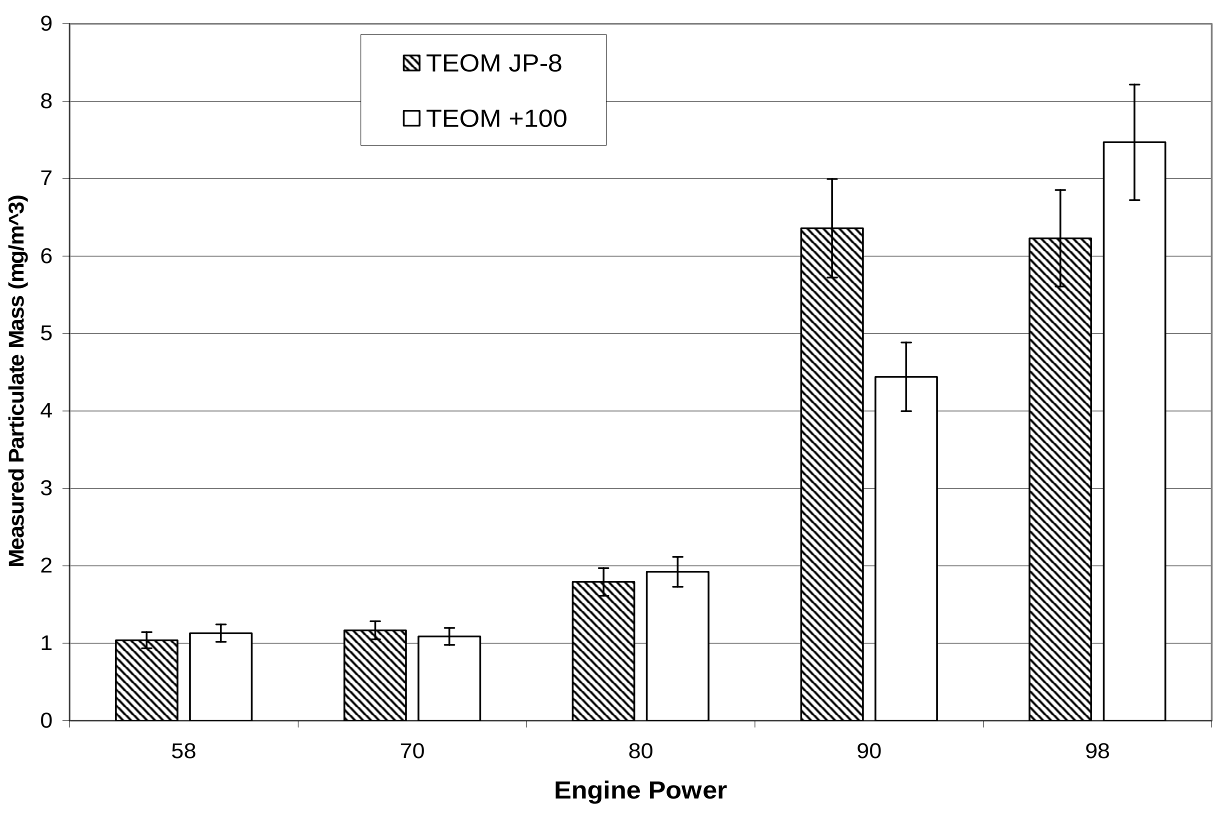


Figure 25. Comparison of TEOM Measured Particulate Mass TF33 Tests II

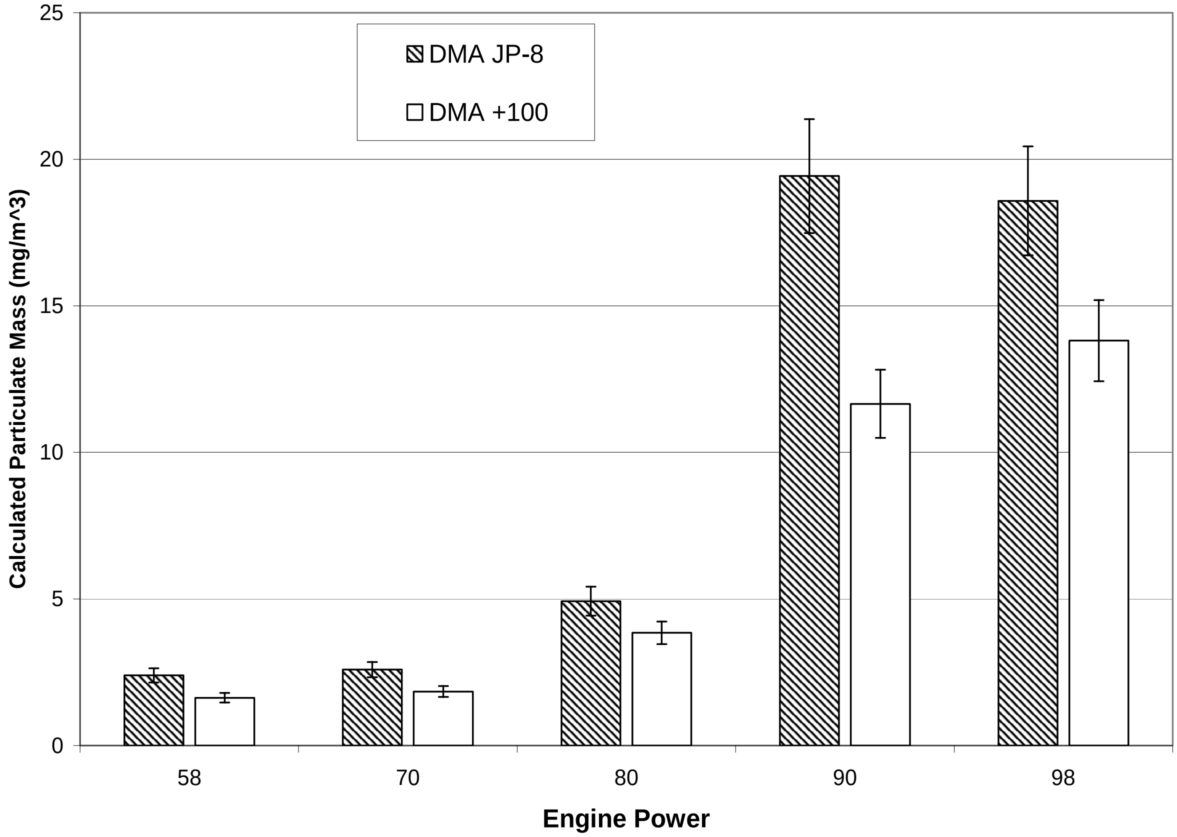


Figure 26. Comparison of Calculated Particulate Mass TF33 Tests II

4.3.3.4 Impact of Fuel Composition and Ambient Conditions on Particulate Emissions

Fuel composition, particularly sulfur and aromatic content, could potentially impact particulate emissions making it more difficult to assess the effects of the +100 additive when the engine is operated with different JP-8 fuels. Since the fuel tank had to be replenished after every 30 cycles, samples of each fuel were taken for subsequent ASTM JP-8 specification tests. Results of the specifications tests of each fuel are shown in Table 4-14. As shown, both the aromatic and sulfur content of the fuels were very similar. Figure 27 displays the PND and the fuel aromatic concentration for each test. From the graph, it is clear that there was no correlation between the fuel aromatic content and engine particulate emissions. The differences in aromatic and sulfur levels between the fuels were relatively minor, which may explain their negligible impact on particulate emissions.

Table 4-14. ASTM JP-8 Specification Tests for fuels used at Barksdale AFB (TF33 II) Tests in Oct. 2003

ASTM Tests	Standard	JP-8 (20 Oct)	JP-8+100 (21 Oct)	JP-8+100 (22 Oct)	JP-8+100 (23 Oct) A	JP-8+100 (23 Oct) B
Total Acid Number, mg KOH/g (D3242)	Max 0.015	0.003	0.006	0.005	0.006	0.004
Aromatics, %vol (D1319)	Max 25.0	12.4	14.7	12.1	13.8	13.1
Total Sulfur, % mass (D4294)	Max 0.30	0.05	0.06	0.07	0.06	0.05
Distillation-Residue, % vol (D86)	Max 1.5	1.2	1.3	1.1	1.1	1.2
Distillation-EP, deg C (D86)	Max 300	246	249	250	249	246
Freezing Point, deg C (D5972)	Max -47	-52	-53	-52	-52	-52
Existent Gum, mg/100mL (D381)	Max 7.0	0.8	7.2	6.8	10.4	8.6
Viscosity @ -20deg C, cSt (D445)	Max 8.0	4.3	4.4	4.5	5.0	4.5
FSII (DiEGME), % vol (D5006)	0.10-0.15	0.13	0.13	0.12	0.14	0.13
Conductivity, pS/m (D2624)	150-600	92	884	843	931	693

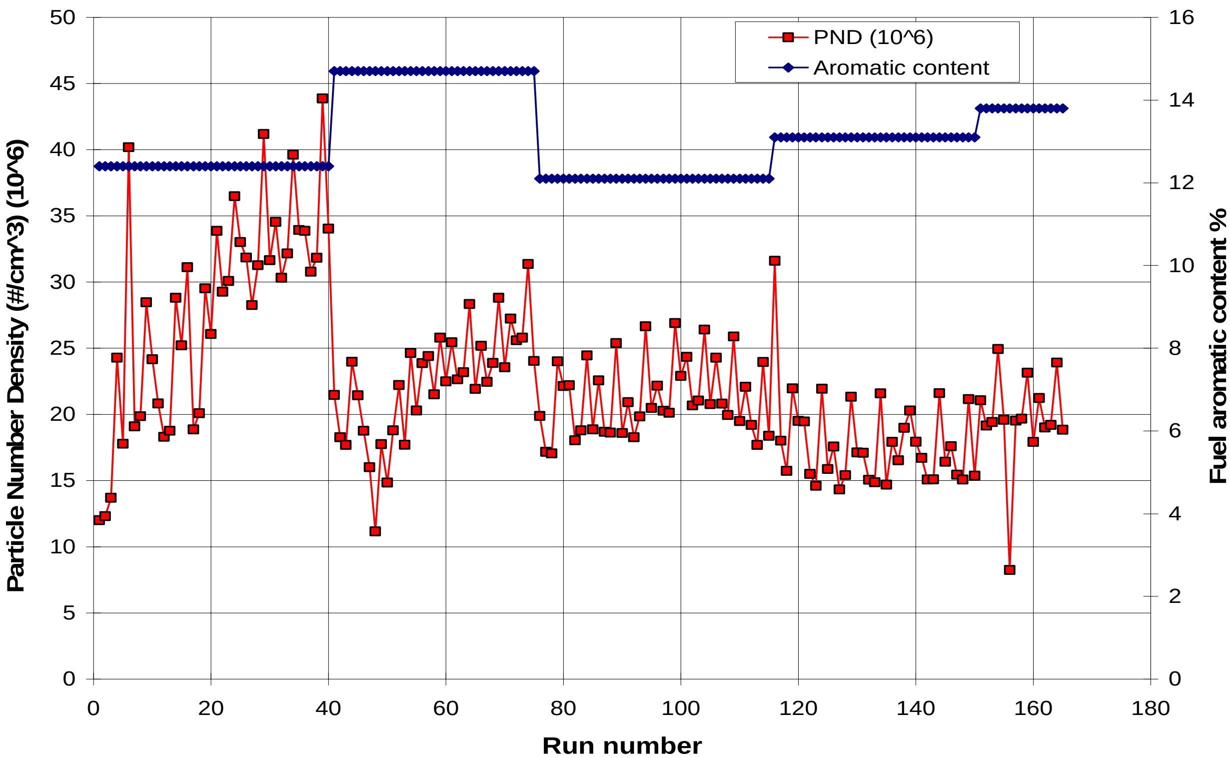


Figure 27. Relation of PND and Fuel Aromatic Content for TF33 test II

Measurements of ambient temperature and relative humidity were made to investigate their potential impact on particulate emissions. The results in Figure 28 show no clear trend or impact of the ambient conditions on particulate emissions. Surprisingly, changes of nearly 100% in relative humidity, measured between runs 80-125, did not appear to impact the engine PND emissions, which were relatively constant.

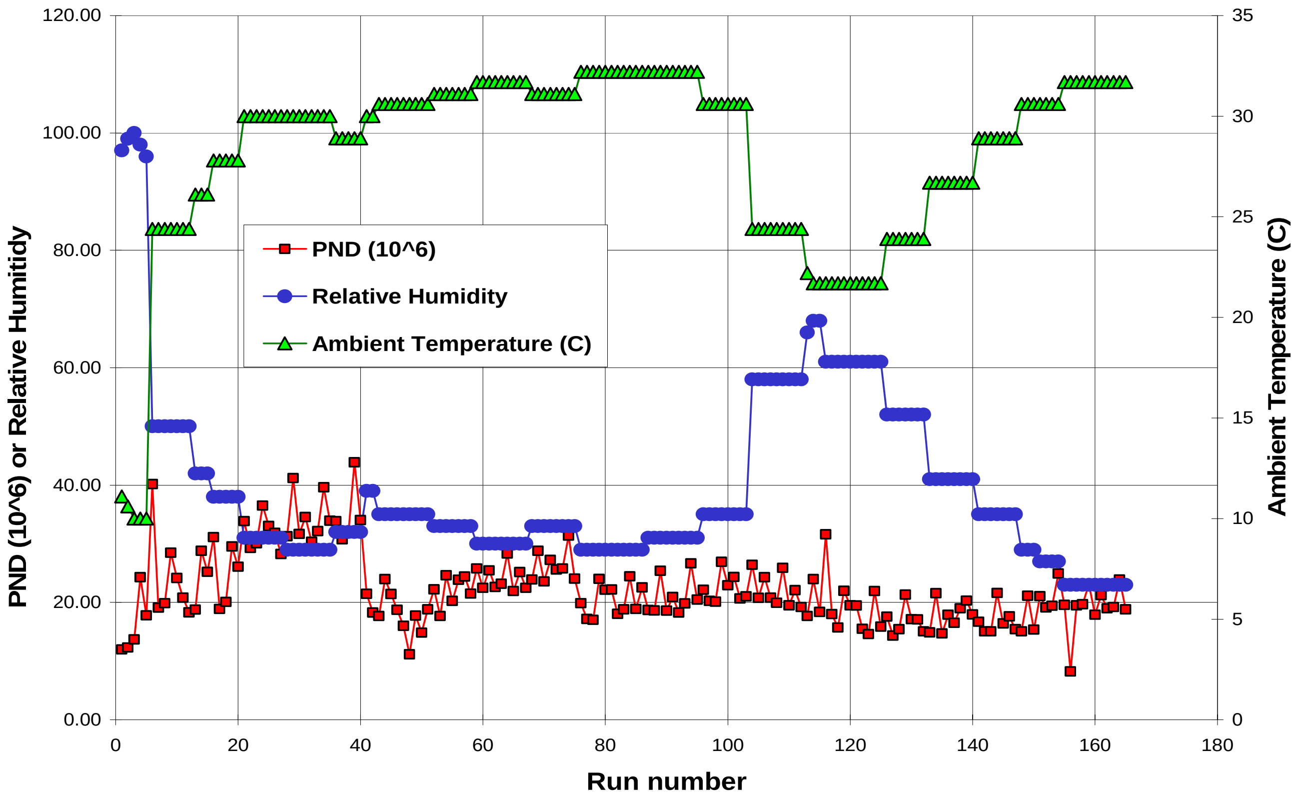


Figure 28. Relation of PND and Atmospheric Parameters for TF33 Test II

4.3.3.5 Gaseous emissions

Gaseous emissions from the TF33 engine were quantified by AFRL scientists using a Horiba FIA-510 total hydrocarbon analyzer, an M&C PMA-10 oxygen analyzer, and an MKS MultiGas 2030 Fourier-Transform Infrared (FTIR) based gas analyzer (Figure 29). The FTIR analyzer is capable of quantifying all non-symmetric gaseous species at parts-per-billion (ppb) to % sensitivity. The Multi-Gas 2030 FTIR software allows for the continuous real-time measurement, display and recording of a sample stream. Results of the gaseous emissions are shown in Table 4-15 for both fuels at different power settings. Reductions of 15-21% in unburned total hydrocarbon (THC) emissions were consistently observed when using JP-8+100 relative to JP-8. At idle, a significant increase in NO emissions were observed with the additive, however, the quantities obtained were in the low end of the instrument measurement range where uncertainties were significant. As observed, with the exception of the THC, the +100 additive had negligible effects on gaseous emissions.

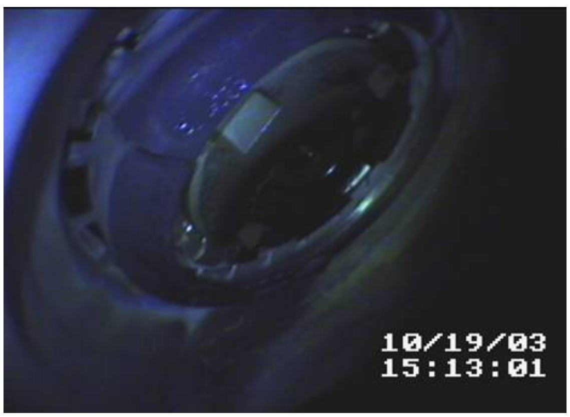
Figure 29. AFRL Gaseous Emissions Analysis System at Barksdale AFB

Table 4-15. Gaseous Emissions for TF33 Test II

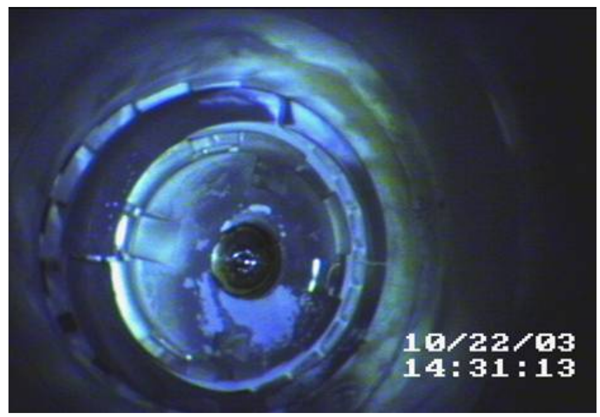
58% Engine Power					
	CO (ppm)	CO2 (%)	NO (ppm)	H2O (%)	THC (ppm)
JP-8	698.85	1.17	2.93	3.54	4992.30
JP-8+100	653.46	1.14	3.98	4.36	4266.50
% Difference	-6.5%	-3.0%	35.7%	23.1%	-14.5%
70% Engine Power					
	CO (ppm)	CO2 (%)	NO (ppm)	H2O (%)	THC (ppm)
JP-8	445.68	1.15	2.84	3.28	2863.00
JP-8+100	451.61	1.19	2.51	3.52	2406.85
% Difference	1.3%	3.4%	-11.5%	7.1%	-15.9%
80% Engine Power					
	CO (ppm)	CO2 (%)	NO (ppm)	H2O (%)	THC (ppm)
JP-8	242.03	1.60	8.53	3.17	863.89
JP-8+100	245.44	1.57	7.46	3.29	700.17
% Difference	1.4%	-1.9%	-12.6%	3.6%	-19.0%
90% Engine Power					
	CO (ppm)	CO2 (%)	NO (ppm)	H2O (%)	THC (ppm)
JP-8	74.05	1.73	31.07	3.51	234.69
JP-8+100	75.47	1.71	30.28	3.30	184.48
% Difference	1.9%	-1.2%	-2.5%	-6.0%	-21.4%
98% Engine Power					
	CO (ppm)	CO2 (%)	NO (ppm)	H2O (%)	THC (ppm)
JP-8	17.84	2.44	84.25	3.32	137.77
JP-8+100	18.24	2.39	84.64	3.21	109.30
% Difference	2.3%	-1.9%	0.5%	-3.2%	-20.7%

4.3.3.6 Borescope Images

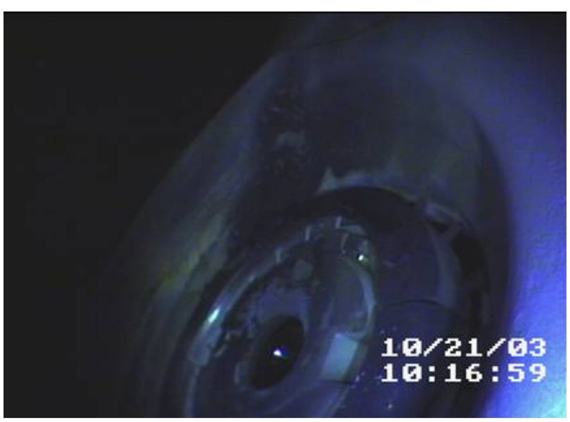
Sections of the TF33 engine were inspected with a borescope after several hours of operation with JP-8 and with JP-8+100 to determine if there was any visible cleanup with the detergent/dispersant additive. Images of one fuel nozzle at different time intervals are shown in Figure 30. Unfortunately, due to difficulty in handling the borescope through the small access holes in the engine, its relative position/angle was not identical for all images which made it difficult to assess differences in soot buildup or clean up. Nonetheless, comparison of the 4.5 and 9.5 hours with JP-8+100, show negligible differences in soot deposit patterns. The apparent cleaner nozzle when using JP-8+100 relative to JP-8 (1.0 hour) could be the result of the different photo angle. Although there is no conclusive evidence of a cleaner fuel nozzle, other engines have been shown to be cleaner after tens or hundreds of hours of using the additive (UTC & C4e, 2000). A cleanup effect was not observed here likely due to the relatively short run times with the additive. This is believed to be the mechanism by which the +100 additive may improve emissions; by maintaining the engine fuel nozzles clean and thus, a uniform fuel spray pattern for optimum engine performance.



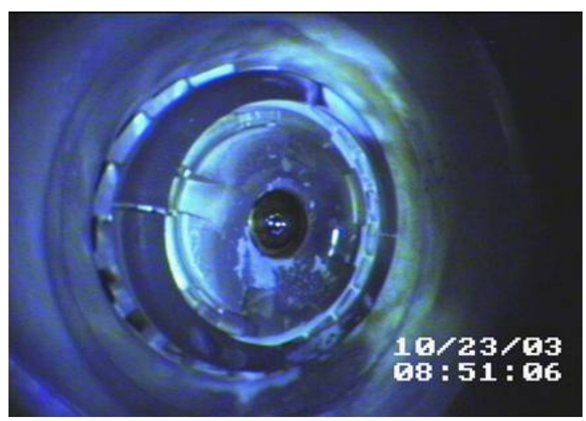
1.0 hour operation with JP-8



4.5 hours operation with JP-8+100



5.0 hours operation with JP-8



9.5 hours operation with JP-8+100

Figure 30. Borescope Images of TF33 Fuel Nozzle During TF33Test II

4.3.3.7 Summary

Particulate and gaseous emissions measurements were performed on a TF33 engine at Barksdale Air Force Base. Test results show an apparent trend of decreased particle concentration on a daily basis for all conditions; however, these reductions were determined to be statistically insignificant. Significant reductions (~30%) were only observed for both TEOM and DMA-based particle mass at the 90% power setting. Although different fuels were used, the aromatic and sulfur content of these were very similar, and therefore, did not play a role in the differences in emissions between the JP-8 and JP-8+100. Engine borescope images showed negligible differences in soot deposit patterns as the additive was continually used. However, longer tests may be required to demonstrate the ability of the additive to maintain engine parts clean, which may eventually improve engine performance.

4.3.4 T63 Tests at Wright-Patterson Air Force Base

4.3.4.1 Description and Objectives

Tests were conducted on a T63 engine to explore the long term effects of the +100 additive on particulate emissions. Previous tests on several turbine engines have shown an apparent improvement in emissions as the additive was continually used. For these tests, the engine was operated initially on JP-8 for 87.5 hours, and then on JP-8+100 for the following 87.5 hours. Particulate and gaseous emissions measurements were made during operation with both fuels. Particulate emissions were captured and transported to the analytical instruments via an oil-cooled probe. The probe was installed facing the flow in the center and near the exit of the engine to help capture a “representative” sample of the engine exhaust and avoid diluting or contaminating with surrounding air. As in the field demonstration, the sample was immediately diluted at the probe tip to help prevent water condensation and particle loss to the wall due to high wall-sample temperature gradients. The diluted sample was drawn into the instruments via a vacuum pump, and the air dilution and sample flows were controlled with high precision flow controllers. A picture of the instrumentation used is shown in Figure 31. The long-duration test followed a predetermined cycle in which the engine was operated at different conditions for a period of time. The test cycle, shown in Table 4-16, had the longest run time at the cruise condition, therefore all emissions data were taken at that condition.

Table 4-16. T63 Long-Duration Tests 175 minutes Cycle

Engine Condition	Time (mins)
Idle	2.0
Cruise	10.0
Idle	2.0
Max.	5.0
Cruise	50.0
Max.	5.0
Idle	0.25

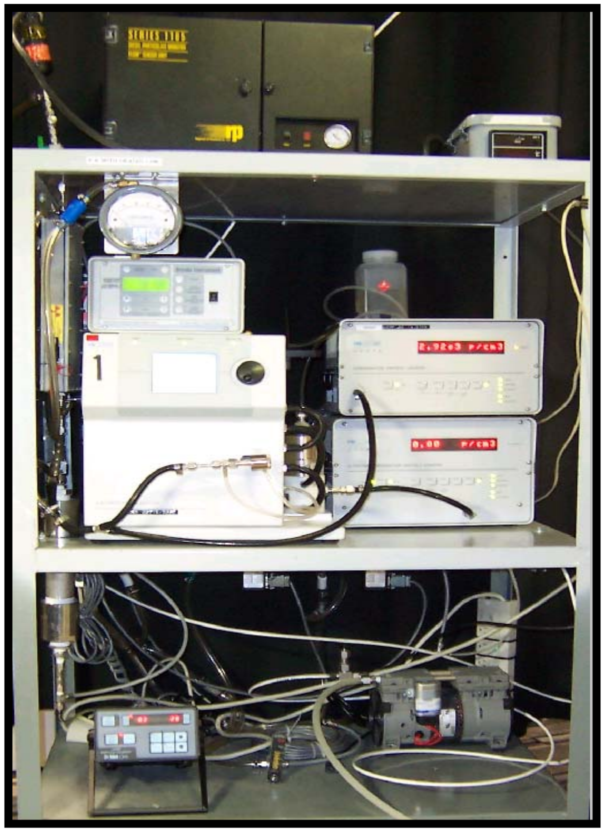


Figure 31. AFRL Particulates Instrumentation

On-line analysis of the particulate emissions was performed primarily using a TSI Model 3022A Condensation Nuclei Counter (CNC) to provide PND, and a TSI Model 3936 Scanning Mobility Particle Sizer (SMPS) to obtain a particle size distribution. A Differential Mobility Analyzer (DMA) TSI Model 3081 was used in the SMPS to classify the particles by size. A Rupprecht & Pataschnick Tapered Element Oscillating Microbalance (TEOM) was used to provide direct real-time measurement of the particulate mass emissions. Sections of the T63 combustor were inspected with a borescope at different time intervals during the tests to assess soot deposits with both fuels. Pictures of the combustor can at several time intervals were also taken.

4.3.4.1 Particle Number Density

PND data as a function of test time for the cruise condition during the long-duration T63 tests are shown in Figure 32. The PND increased by nearly 50% from 13 to 48 hours of operation with JP-8. This is believed to be the result of fuel nozzle fouling, which potentially caused non-uniform fuel spray and eventual degradation of the combustion performance. Continuous use of the baseline fuel did not further degrade/increase engine particulate emissions. After 87.5 hours of test time, JP-8+100 was used. As shown, the +100 additive did not effect a change in PND until after 40 hrs of use in which a marginal reduction of 15% was observed. Further use of the additive had negligible effect on the PND.

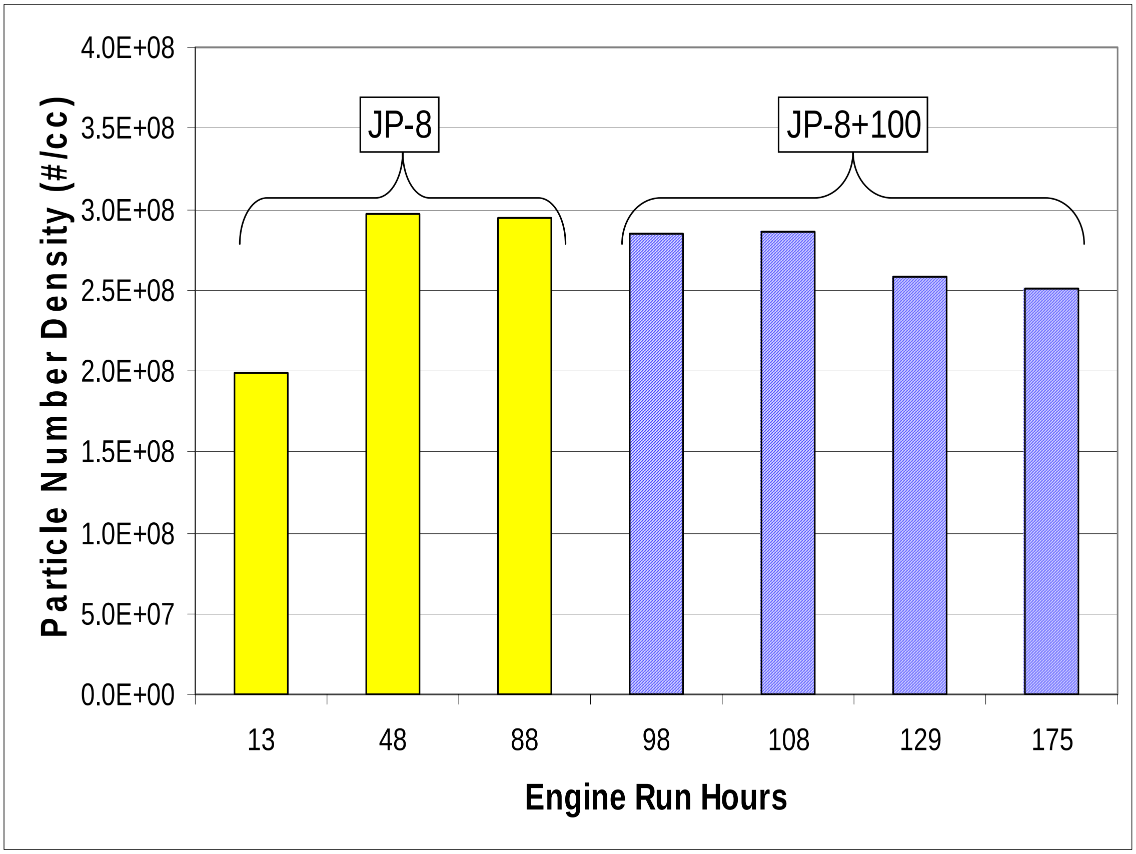


Figure 32. Particle Number Density for Long-Duration Tests on T63 engine

4.3.4.2 Particle Size Distribution

The particle size distribution for baseline JP-8 and JP-8+100 tests are shown in Figure 33. At 13 hrs the concentration of particles was significantly lower than for the other cases. The mean particle diameter for the baseline and +100 runs were very similar for all test runs. The concentration of particles peaked at the 88 hr mark and decreased slowly with use of the additive. Consistent with the PND data, negligible differences were observed between the 129 and 175 hrs size distribution and trends, thus no changes in mass occurred during this time period.

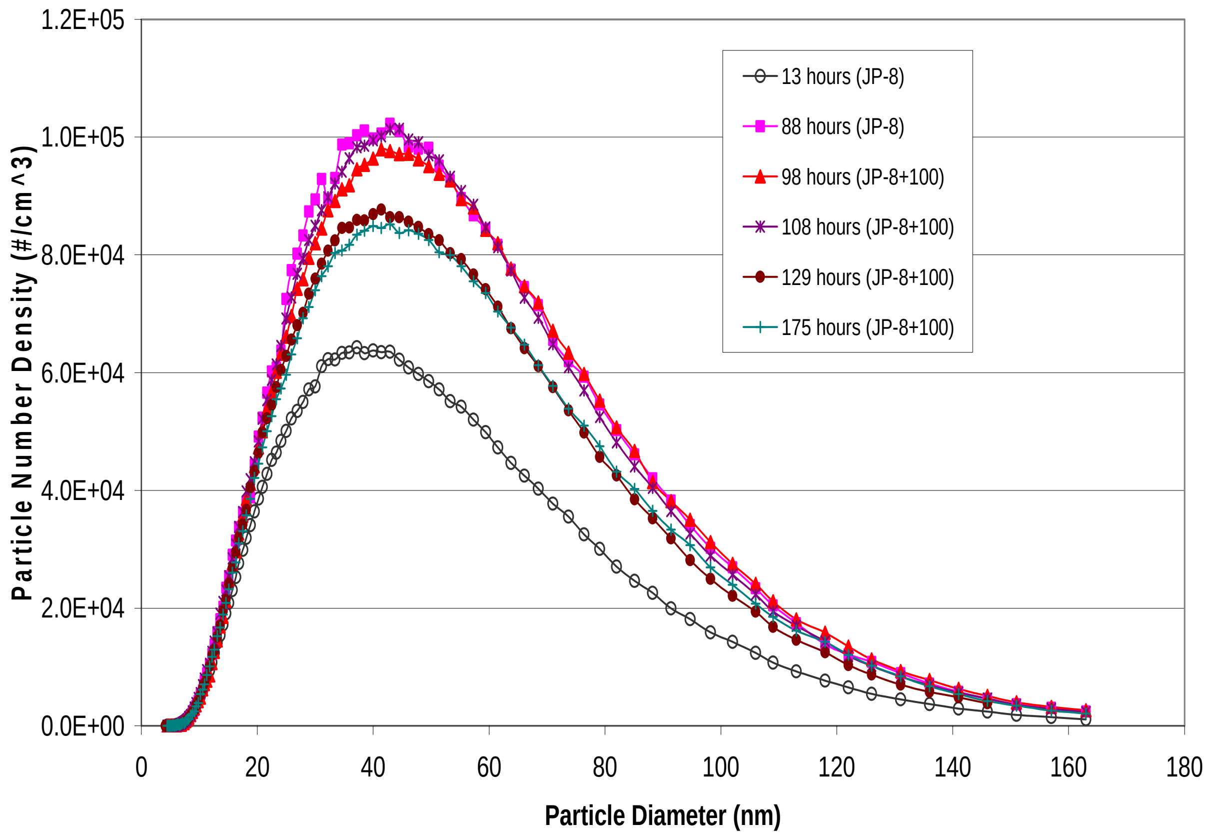


Figure 33. Particle Size Distribution for Long-Duration T63 Tests

4.3.4.3 Particulate Mass based on TEOM

Direct particulate mass measurements from the T63 using a TEOM are shown in Figure 34. Lower particulate mass was observed at 13 hrs of operation with JP-8 which is consistent with the PND and particle size distribution data, however, this data point was considered invalid since the sampling line was unheated, which could have caused particle losses. The remaining data showed negligible changes as the engine operated continuously with the additive. Therefore, no measurable effect on particulate mass emissions was observed with the additive despite being used in the T63 engine for nearly 88 hours. It is noteworthy that the T63 was expected to be less sensitive to a potential improvement in particulate emissions with the +100 additive since it is a single fuel nozzle engine. Multi-fuel nozzle engines are expected to benefit more of the detergent capabilities of the additive due to the propensity of fuel nozzles to foul or coke-up.

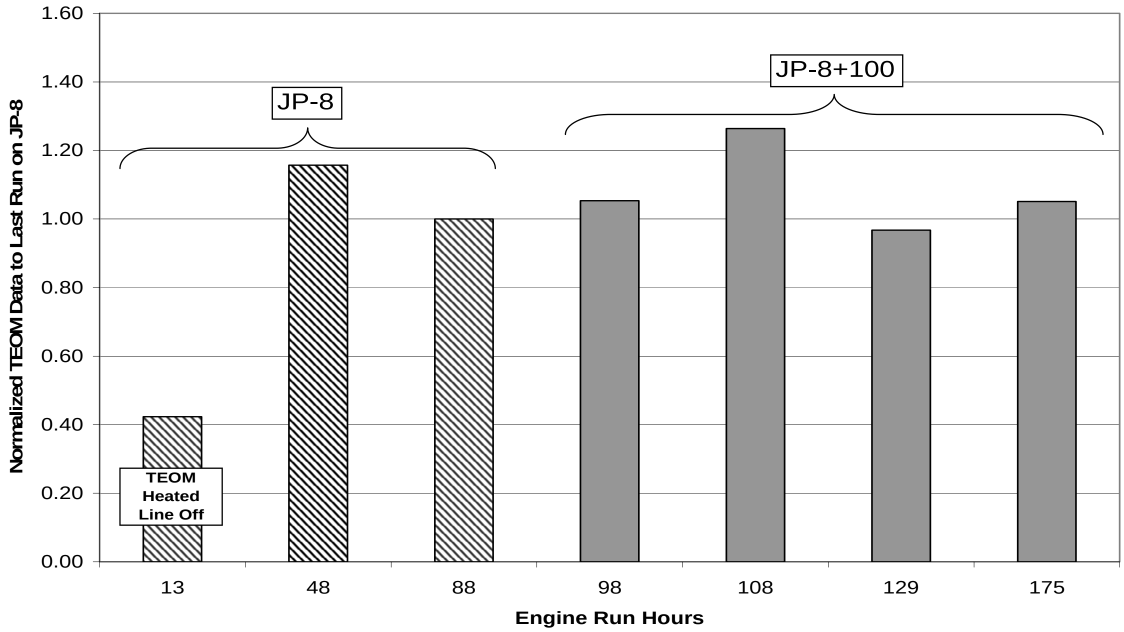


Figure 34. Mass of Particulate Emissions for Long-Duration T63 Tests at Cruise Condition

4.3.4.4 Gaseous emissions on T63

Measurements of gaseous species including: CO, CO_2, NO_x and SO_x showed no effect of the +100 additive at the two conditions tested. Also, no long-term effects on emissions were observed. Consistent with results of the second TF33 engine tests, reductions in THC were observed with the additive. Reductions in the range of 25-30% in THC were observed at the cruise condition (see Figure 35). The agreement between the T63 and TF33 increases confidence that the additive may indeed have the capability of reducing THC emissions in different type engines.

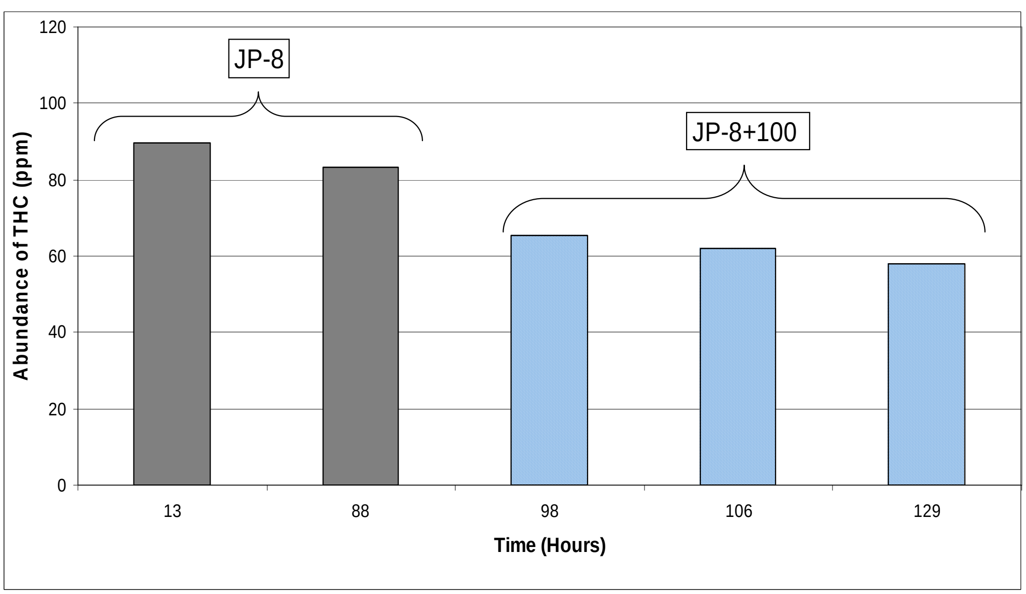


Figure 35. Total Unburned Hydrocarbons for Long-Duration T63 tests at Cruise condition

4.3.4.3 T63 Borescope and Combustor Pictures

Borescope images of the T63 combustor were taken at different time intervals during the long-duration tests. Unfortunately, due to poor lighting, the images were not clear and thus inconclusive. Shown in Figure 36 are pictures of two T63 combustors from a previous demonstration showing the sooting patterns within the combustor with the engine operating on baseline JP-8 for 45 hours and on JP-8+100 for 175 hours. The combustor is visibly much cleaner with the use of the additive despite operating for an additional 130 hours. As mentioned previously, particulate measurements in this demonstration program showed no evidence of improved emissions using the +100 additive. Clearly, from the images in Figure 36 there are definite reductions in soot emissions with the additive. Since the CNC measures engine PND without discriminating the composition of the particles, it is plausible that the soot yield is reduced with the additive but an increase in particles via additive by-products may occur, thus counteracting the reduction in soot emissions. An argument challenging this hypothesis is that the chemical characterization of the particles during the TF33 tests showed no discernable differences between particles produced with and without the additive. Also, for these tests there appears to be negligible change in the particle size distribution when the additive is injected. It would be unlikely for the additive by-products to have similar physical characteristics as the soot particles. Further research in this area is warranted.

Figure 36. Soot Buildup in two T63 Combustors from a Previous Demonstration Operated 45 hrs on JP-8 and 175 hrs on JP-8+100

5. Cost Assessment

5.1 Cost Reporting

The operational costs for the +100 additive conversion of the T-43 and B-52 aircraft at Randolph and Barksdale AFB respectively are mostly due to the cost of the additive. All other potential costs are considered minor. A summary of these operational and the implementation costs is presented in Table 5-1.

Table 5-1. +100 Additive Operational and Implementation Costs for T-43 and B-52 Aircraft

	Direct Costs			
	Start-Up		Operation and Maintenance	
Aircraft/Air Force Base	**Activity**	**$**	**Activity**	**$**
T-43/Randolph AFB	Additive Injection System	$ -	*Additive per yr	$ 18,200.00
	Defuel Trucks		Defueling Operations	0
	Additive Storage Tanks	$ 15,000.00		
	Installation	$ -		
	Total	**$ 15,000.00**		**$ 18,200.00**
B-52 Barksdale AFB	Training Operators	$ 6,000.00	*Additive per yr	$208,000.00
	Additive Injection System	$ 52,500.00	Defueling Operations	
	Defuel Trucks	$145,000.00		
	Storage Tanks & Misc.	$ 15,000.00		
	Site Verification	$ 11,250.00		
	Installation	$ 21,000.00		
	Travel & Mobilization	$ 13,000.00		
	Total	**$ 263,750.00**		**$208,000.00**

***Additive cost based on average annual fuel consumption multiplied by $0.005 per gallon JP-8 fuel

5.2 Cost Analysis

Based on experience with fighter and cargo aircraft presently using the +100 additive, reduced coking of fuel nozzles and therefore, reduced maintenance due to fuel nozzle and combustor anomalies are expected with the use of the additive. However, for this demonstration the aircraft or engines were operated with the additive for only one week, which did not allow sufficient time to conduct a long-term (several years) study on the maintenance benefits of the additive. Since these benefits are highly dependent on engine type and operation, it is impossible to properly estimate potential cost savings in maintenance (e.g. time between engine overhauls) and increased engine life produced by the additive without a long-term study. Since consistent benefits in emissions were not observed in this program, the additive appears to offer no cost benefits in these platforms.

5.2.1 Implementation Costs for B-52 Aircraft at Barksdale AFB, LA

A study conducted by Mr. Ozzie Pinkham of C4e Inc. (on contract with AFRL/PRTG) identified four options for the implementation of the +100 additive at Barksdale AFB for use in the B-52 aircraft. Options and associated costs are described in Appendix A.

5.2.2 Implementation Costs for T-43 Aircraft at Randolph AFB, TX

Based on discussions with base officials, there will be no cost for implementation of the +100 additive on the T-43A trainer aircraft at Randolph AFB. Since the base already operates smaller trainers (e.g. T-37s, T-38s) with JP-8+100, the infrastructure required to support the additive use in the T-43 aircraft (e.g. additive injection carts, refueler trucks, etc.) is already in place. Costs associated with the increased workload as the result of additive injection is expected to be minimal. An additional defueling truck might be required to facilitate the aircraft defuels. The use of the additive may actually simplify on-base defueling operations since there will not longer be a need to have separate defueling tanks for JP-8 and JP-8+100. Details about implementation of the additive for T-43 planes in Randolph are discussed in Appendix B.

6. Implementation Issues

6.1 Environmental Permits

For the present demonstration no special environmental permits were required for the use or disposal of the +100 additive. Waste streams were not generated during the demonstration. Any quantity of additive remaining after the demonstration was shipped back to Wright-Patterson AFB and safely disposed using established procedures.

6.2 Other Regulatory Issues

There are no known regulations that apply to this technology for future demonstrations.

6.3 End-User/Original Equipment Manufacturer (OEM) Issues

A study conducted by C4e Inc. to investigate the feasibility of converting the existing fleet of T-43A aircraft at Randolph AFB to JP-8+100 was completed (Appendix B). C4e Inc. conducted research into the T-43's flight missions and the refueling/defueling history to determine if these were major issues in the implementation of +100 in these aircraft. The study showed that defueling operations with this aircraft were not a major issue since defuels were minimum and usually occurred on station. Therefore, there appear to be no major issues to the implementation of the additive in the T-43. However, further coordination and acceptance from the aircraft SPO and Boeing will be required before the AETC grants the approval to convert the T-43 fleet to use the +100 additive.

Implementation of the +100 additive on the B-52 is more challenging since the aircraft lands in bases not equipped to handle the additive. Tests have shown that the additive disarms filter coalescers (Edition 3), resulting in the need of high blend back ratios (currently set at 100 gallons JP-8 per gallon of JP-8+100) to prevent the filter problems. This complicates the implementation of the additive in locations not equipped (e.g. defuel tanks and refueling trucks) to handle the additive. Specific issues with implementing the additive at Barksdale AFB are addressed in Appendix A. Additive implementation on the B-52 will need to be approved by the airframer (Boeing), the Air Force Petroleum Office (AFPET), the B-52 SPO and base officials.

Based on this demonstration, the increased cost and logistics burden associated with using the +100 additive in these platforms cannot be justified since no clear (or sufficient) benefits in emissions were observed. However, a more extensive program should be established on these aircraft to study the potential benefits of the additive on reduced engine maintenance as has been observed in other platforms.

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8. Points of Contact

Point of Contact Name	Organization Address	Email	Role in Project
Edwin Corporan	AFRL/PRTG 1790 Loop Rd N WPAFB, OH 45433	edwin.corporan@wpafb.af.mil	Principal Investigator
Phil Whitefield	University of Missouri-Rolla G-7 Norwood Hall 1870 Miner Circle Rolla, MO 65409-0430	pwhite@umr.edu	Aircraft Particulate Measurements

Appendix A

Implementation Costs of +100 additive for B-52 Aircraft at Barksdale AFB

OPTION 1
Install pipeline additive injection system on one of two hydrant Type III refueling systems:

Cost factors:

Site Determination/ Verification Visit:
135 man hours @$75.00 = $10,125 includes ordering equipment, coordinating equipment shipments and obtaining permits and work passes.

Equipment Options:
Option 1. Hammond's meter and pulsar electronic injection system cost approximately $9,000 (Existing Meter Must be Available)

Option 2.Hammond's in-line fluid driven injector with smart control system cost approximately $20,000

Concrete pad and 3,000 gallon double wall storage tank, transfer pump and electrical equipment cost approximately $15,000

Installation Cost:
240 man hours @$75.00 = $18,000

Travel and Mobilization Expenses $12,000

Total Cost for Option 1 is between $64,125 and $75,125 depending on the type of injection system.

Pros/ Cons: Allows for aircraft with JP-8+100 to be defuel back into the hydrants system. Limits accessibility to JP-8+100 to only one aircraft parking ramp.

OPTION 2.
Install truck mounted injectors on all ten of the hydrant servicing vehicles.

Cost factors:

Site Determination/Verification Visit:
120 man hours @$75.00 = $9,000 to including ordering equipment, coordinating equipment shipments and obtaining permits and work passes.

Equipment Options;

Gammon truck mounted air driven injection system with two 10 gallon stainless steel tank cost approximately $6,500 each 10 X $6,500= $65,000

Concrete pad and 3,000 gallon double wall storage tank, pump and electrical equipment cost approximately $15,000

Installation Cost:
320 man hours @$75.00 = $24,000

Travel and Mobilization Expenses $13,000

Total Cost for Option 2 is approximately $126,000.

Pros/Cons: Provides for great accessibility to JP-8+100, but limits defueling capability to truck defuels only.

OPTION 3
Install pipeline additive injection system on one of two hydrant Type III refueling systems and truck mounted injectors on five of the hydrant servicing vehicles

Cost factors:

Site Determination/Verification Visit:
150 man hours @$75.00 = $11,250 to including ordering equipment, coordinating equipment shipments and obtaining permits and work passes.

Equipment Options;
Option 1) Hammond's meter and pulsar electronic injection system cost approximately $9,000 (Existing Meter Must be Available)
Option 2) Hammond's in-line fluid driven injector with smart control system cost approximately $20,000

Gammon truck mounted air driven injection system with two 10 gallon stainless steel tank cost approximately $6,500 each 5 X 6,500= $32,500

Concrete pad and 3,000 gallon double wall storage tank, transfer pump and electrical equipment cost approximately $15,000

Installation Cost:
280 man hours @$75.00 = $21,000

Travel Expenses $13,000

Total Cost for Option 3 is between $101,750 and $112,750 depending on the type of injection system.

Pros/Cons: Provides the most accessibility to JP-8+100 and allows flexibility for both refueling and defueling operations. This option is more costly than Option 1; however it's less costly than option 2.

OPTION 4

Install pipeline injection systems on both hydrant refueling systems

Cost assessment was not completed because it was not deemed operationally feasible to have both systems with JP-8+100 and no hydrant capability for transient aircraft not using the +100 additive.

Appendix B

Implementation Costs of +100 additive for T-43 Aircraft at Randolph AFB

Universal Technology Corporation

And The

Air Force Research Laboratory

April 2002

1.0 Introduction and Background

Air quality is a major concern throughout the United State and most other countries. With the growth of industrial nations throughout the world, the release of airborne particulate emissions into the atmosphere has greatly increased. Airborne particulate emissions pose both a health and environmental risks. These airborne particular matter inhaled into the respiratory system are known factors for various respiratory problems. Airborne particulate emissions effect the daily environment causing reduced visibility due haze in the atmosphere.

It is estimated that the aviation industry in the United States generates some 3 million kg of particulate emissions per year from gas turbine engines on aircraft and ground support equipment. Military aircraft contributes approximately 600,000 kg of the particulate emissions release into the atmosphere. The Air Force Research Laboratory has demonstrated that the use of the +100 (BetzDearborn SpecAid 8Q462) additive reduces coking deposits in aircraft engine components. The +100 additive used to increase thermal stability of fuel has been injected into the JP-8 jet fuel of fighter and trainer aircraft since 1996. The +100 additive consists of a detergent dispersant, a metal deactivator, and an antioxidant. Aircraft engine analysis reflects that engines operating on JP-8 with the +100 additive (JP-8+100) have significantly less soot built up than those engines operating on straight JP-8.

2.0 Objective

The Air Force Research Laboratory has estimated that military transport aircraft could reduce particulate emissions by 90,000 kg per year by using the +100 additive. If further research shows this to be case, than the use of the +100 additive could significantly reduce the particulate emissions generated by the commercial aviation industry as well. The Air Force operates ten, T-43 aircraft for navigation and pilot training at Randolph AFB in San Antonio, Texas. The T-43 aircraft is a converted Boeing 737 commercial airline equipped with two Pratt &Whitney JT-9D engines. The Air Force Research Laboratory is currently considering conducting an analysis of the T-43 aircraft using the +100 additive. C4e was requested by AFRL to conduct research into the T-43's flight missions and the refueling/defueling history.

3.0 T-43 Flight Missions

Air Education and Training Command, 12th Flying Training Wing at Randolph AFB is responsible for aircraft navigational training. The 562nd Squadron operates ten, T-43A aircraft commonly referred to as Gator. These aircraft are Boeing 737s that have been modified as flying classrooms for student enrolled in aircraft navigation training and pilot training. The 562nd Squadron conducts approximately four navigational training flights daily and three pilot training flights weekly. The navigational missions normally begin and end at Randolph AFB; the aircraft routinely does not land at any location other than Randolph for fuel. The

average fuel load at take-off on the T-43 for a navigational mission is approximately 35,000 pounds (5,147 US Gallons) of JP-8 turbine fuel jet. The aircraft lands with approximately 6,000 pounds (882 US Gallons). The navigational mission's duration is approximately 4 hours in length. The 562nd Squadron also conducts pilot training with the T-43 three times a week. The pilot training mission is normally 5 hours in length. However, unlike the navigational missions, the pilot training mission the T-43 sometimes land at other locations over night and may require to be refueled prior to returning to Randolph AFB.

3.1 T-43 Maintenance

Civil service employees provide the daily routine maintenance on the ten, T-43s that were manufactured between 1971 and 1973. Depot Maintenance for the T-39 is performed under a contract with Boeing at Waco, Texas, where the aircraft under goes FAA certification. The engine depot maintenance is under contract with AeroThrust in Miami, Florida. The T-43 flight scheduler indicated that the aircraft are identified by tail number for missions and depot maintenance repair approximately a week in advance.

3.2 Aircraft Utilization Rate

All ten aircraft have relatively low flying hours for their age. Table 1 depicts the Aircraft Utilization Rate (AUR) Monthly Data for the month of March 2002 to include the total hours of each aircraft.

AUR MONTHLY DATA MARCH 2002

Table 1

ORG	COMMAND	BASIC	UTIL		
	CODE	COMMAND	PEC		
12FTW	AETC	AETC	84742F		
UTIL	FLYING	NUMBER OF	NUMBER OF	TOUCH	AIRCRAFT
CODE	HOURS	SORTIES	LANDINGS	& GO'S	HOURS
03YN	0.8	1	1		
T1AN	12.6	3	3		
T1LN	4.5	1	2		
T3MN	9.7	2	20		
T3NN	1	1	2		
	28.6	8	28	20	19670.4
T1AN	23.8	6	9		
T1BN	8.3	2	2		
T1LN	22.7	7	28		
T1VN	2.9	2	5		
T3MN	13.8	5	21		
T3NN	15	4	4		
T3ON	3.8	2	2		
	90.3	28	71	43	19466.9
T1AN	8.2	2	2		
T1LN	8	2	9		

T3MN	4.9	1	1		
	21.1	5	12	7	18708.6
	0	0	0	0	20584.8
O8YN	3.2	2	2		
T1AN	8.5	2	3		
T1ON	3.7	2	2		
	15.4	6	7	1	18217.2
T3NN	1.1	1	1		
	1.1	1	1	0	18346.6
O8YN	2.1	1	1		
T1AN	21	6	6		
T1LN	9	2	16		
T1ON	17.2	5	5		
T3MN	3.2	1	1		
T3NN	0.8	1	1		
	53.3	16	30	14	18925.5
T1AN	49.2	12	13		
T1LN	3.9	1	1		
T1ON	16.2	4	4		
T3FN	1.2	1	1		
T3MN	15.3	3	25		
	85.8	21	44	23	19933.1
O8CN	2.1	1	1		
O8YN	5.4	3	3		
T1AN	16.5	4	5		
T1LN	2	1	1		
T1ON	3.9	1	1		
T3MN	9.4	2	2		
T3VN	3.3	1	11		
	42.6	13	24	11	20175.3
T1AN	41.5	10	10		
T1BN	8.3	2	2		
T1ON	4.1	1	1		
T3CN	4.7	2	2		
T3MN	15.6	5	5		
	74.2	20	20	0	17608.4
	412.4	118	237	119	

4.0 T-43 Fueling History

Research was conducted into the past history of T-43's refuels and defuels totaling 3.3 millions US gallons. The data analyzed was from the period of June 2001 thru March 2002. Aircraft fueling records before June 2001 were not available due to the conversion to a new fuels data base system. The data for the past 10 months reflected a total of 1346 refuels of which 56 refuels were accomplished at locations other than Randolph AFB. The refuel quantities range from 57 to 4856 US Gallons. Table 2 lists the off station refueling locations and if JP-8+100 was available at that site. Because of the disarming action of the +100 additive on filter coalescer elements off station defuels were a major concern. The fueling data indicated that the T-43 fleet had been defueled 39 times in the past 10 months all of which occurred at Randolph AFB. The defuel quantities ranged from 146 to 5095 US Gallons. Table 5 lists each defuel by aircraft tail number.

T-43 OFF STATION REFUELS

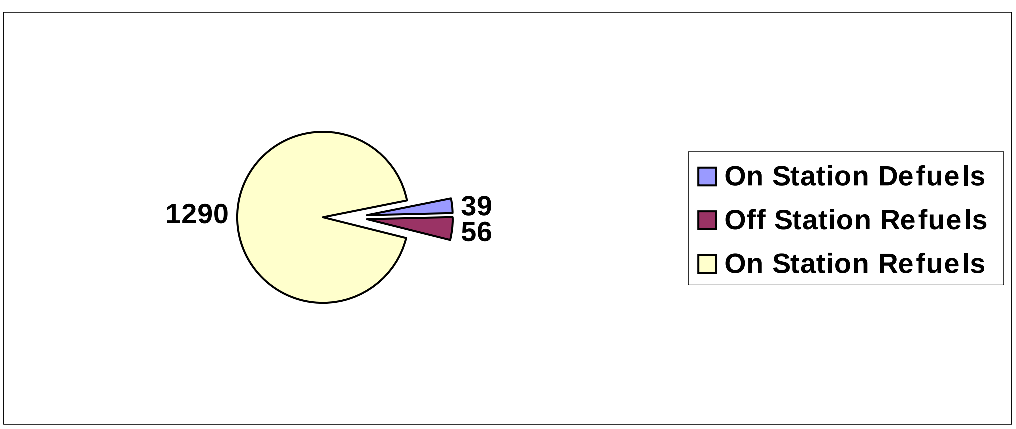
Table 2

MDS	GRADE	QUANTITY	SELLER	FUELING LOCATION	JP-8+100
T043A	JP8	1798	FP2037	TINKER AFB	NO
T043A	JP8	1753	FP2037	TINKER AFB	NO
T043A	JP8	2786	FP2500	PETERSON AFB	NO
T043A	JP8	3660	FP2500	PETERSON AFB	NO
T043A	JP8	1575	FP2500	PETERSON AFB	NO
T043A	JP8	2927	FP2520	PATRICK AFB	NO
T043A	JP8	1830	FP2520	PATRICK AFB	NO
T043A	JP8	2785	FP2805	EDWARD AFB	YES
T043A	JP8	3758	FP2805	EDWARD AFB	YES
T043A	JP8	4477	FP2805	EDWARD AFB	YES
T043A	JP8	4005	FP2823	EGLIN AFB	YES
T043A	JP8	2898	FP2823	EGLIN AFB	YES
T043A	JP8	1804	FP3022	COLUMBUS AFB	YES
T043A	JP8	1004	FP3047	LACKLAND AFB	YES
T043A	JP8	404	FP3047	LACKLAND AFB	YES
T043A	JP8	2617	FP4417	HURLBURT FIELD AFB	NO
T043A	JP8	2009	FP4417	HURLBURT FIELD AFB	NO
T043A	JP8	3249	FP4418	CHARLESTON AFB	NO
T043A	JP8	3509	FP4427	TRAVIS AFB	NO
T043A	JP8	3522	FP4427	TRAVIS AFB	NO
T043A	JP8	4067	FP4427	TRAVIS AFB	NO
T043A	JP8	3000	FP4427	TRAVIS AFB	NO
T043A	JP8	3401	FP4427	TRAVIS AFB	NO
T043A	JP8	2047	FP4469	KIRTLAND AFB	YES
T043A	JP8	2936	FP4479	MCCORD AFB	NO
T043A	JP8	3187	FP4479	MCCORD AFB	NO
T043A	JP8	1441	FP4600	OFFUTT AFB	NO
T043A	JP8	1693	FP4625	WHITEMAN AFB	NO
T043A	JP8	3306	FP4686	BEALE AFB	NO

T043A	JP8	2707	FP4686	BEALE AFB	NO
T043A	JP8	2722	FP4686	BEALE AFB	NO
T043A	JP8	2941	FP4686	BEALE AFB	NO
T043A	JP8	2429	FP4800	LANGLEY AFB	YES
T043A	JP8	3592	FP5518	MILDENHALL AFB	NO
T043A	JP8	3684	FP6181	BANGOR, ME ANG	NO
T043A	JP8	3486	FP6223	ALPENA, MI ANG	NO
T043A	JP8	3391	FP6371	PORTLAND, OR ANG	YES
T043A	JP8	2155	FP6606	WESTOVER, MA ARS	NO
T043A	JP8	2952	FP6648	HOMESTEAD, FL ARS	YES
T043A	JP8	3036	FP6648	HOMESTEAD, FL ARS	YES
T043A	JP8	3993	FP6670	NIAGARA FALLS, NY ARS	NO
T043A	JP8	3237	FP6712	PITTSBURGH, PA ARS	NO
T043A	NAA	4641	KCNW	COMMERCIAL AIRPORT	NO
T043A	NAA	1928	KCNW	COMMERCIAL AIRPORT	NO
T043A	NAA	932	KCNW	COMMERCIAL AIRPORT	NO
T043A	NAA	4540	KCNW	COMMERCIAL AIRPORT	NO
T043A	NAA	2515	EGXJ	COMMERCIAL AIRPORT	NO
T043A	JP8	1404	N00206	NEW ORLEAN JRB	NO
T043A	JP5	2970	N00246	NAS NORTH ISLAND	NO
T043A	JP5	3188	N00246	NAS NORTY ISLAND	NO
T043A	JP5	3043	N00246	NAS NORTH ISLAND	NO
T043A	JP5	3106	N00246	NAS NORTH ISLAND	NO
T043A	JP5	2652	N00246	NAS NORTH ISLAND	NO
T043A	JP5	2097	N00246	NAS NORTH ISLAND	NO
T043A	JP5	2804	N00246	NAS NORTH ISLAND	NO
T043A	JP5	3090	N00246	NAS NORTH ISLAND	NO
Total		**156683**			

TOTAL NUMBER OF FUELING TRANSACTIONS

Table 3



GALLONS OF FUEL SERVICED

Table 4

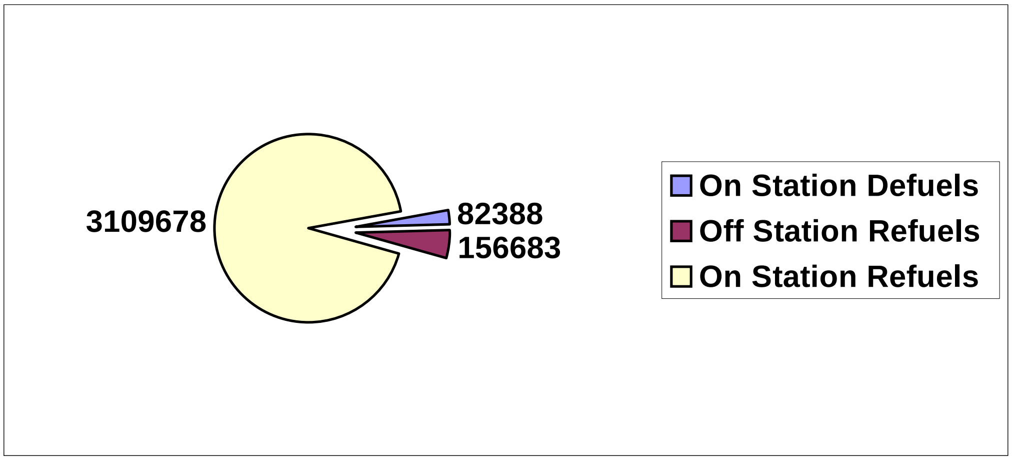

3109678
82388
156683
On Station Defuels
Off Station Refuels
On Station Refuels

Table 5

T-43 DEFUELS

MDS	GRADE	QUANTITY	BUYER		LOCATION
T043A	JP8	2158	FP3089		RANDOLPH AFB
T043A	JP8	1059	FP3089		RANDOLPH AFB
T043A	JP8	1764	FP3089		RANDOLPH AFB
T043A	JP8	1426	FP3089		RANDOLPH AFB
T043A	JP8	570	FP3089		RANDOLPH AFB
T043A	JP8	1593	FP3089		RANDOLPH AFB
T043A	JP8	2202	FP3089		RANDOLPH AFB
T043A	JP8	1417	FP3089		RANDOLPH AFB
T043A	JP8	2048	FP3089		RANDOLPH AFB
T043A	JP8	146	FP3089		RANDOLPH AFB
T043A	JP8	1927	FP3089		RANDOLPH AFB
T043A	JP8	806	FP3089		RANDOLPH AFB
T043A	JP8	331	FP3089		RANDOLPH AFB
T043A	JP8	3641	FP3089		RANDOLPH AFB
T043A	JP8	916	FP3089		RANDOLPH AFB
T043A	JP8	1579	FP3089		RANDOLPH AFB
T043A	JP8	2455	FP3089		RANDOLPH AFB
T043A	JP8	2902	FP3089		RANDOLPH AFB
T043A	JP8	2309	FP3089		RANDOLPH AFB
T043A	JP8	2002	FP3089		RANDOLPH AFB
T043A	JP8	2487	FP3089		RANDOLPH AFB
T043A	JP8	4182	FP3089		RANDOLPH AFB
T043A	JP8	5095	FP3089		RANDOLPH AFB
T043A	JP8	4374	FP3089		RANDOLPH AFB
T043A	JP8	2630	FP3089		RANDOLPH AFB
T043A	JP8	2546	FP3089		RANDOLPH AFB
T043A	JP8	2858	FP3089		RANDOLPH AFB
T043A	JP8	1027	FP3089		RANDOLPH AFB
T043A	JP8	3153	FP3089		RANDOLPH AFB
T043A	JP8	2869	FP3089		RANDOLPH AFB
T043A	JP8	2815	FP3089		RANDOLPH AFB
T043A	JP8	2977	FP3089		RANDOLPH AFB
T043A	JP8	2118	FP3089		RANDOLPH AFB
T043A	JP8	565	FP3089		RANDOLPH AFB
T043A	JP8	1610	FP3089		RANDOLPH AFB
T043A	JP8	2660	FP3089		RANDOLPH AFB
T043A	JP8	746	FP3089		RANDOLPH AFB
T043A	JP8	2165	FP3089		RANDOLPH AFB
T043A	JP8	2260	FP3089		RANDOLPH AFB
Total		**82388**			

Appendix C: Data Quality Assurance/Quality Control Plan

Particulate emissions data were collected from TF33, JT8D-9A and T63 engines using techniques and instrumentation currently used by several research organizations in academia, industry and government (SAE, 2004). Since there is no standard technique to measure particulate emissions from aircraft, this demonstration relied entirely on state-of-the-art instrumentation for measuring aerosol emissions. The performance of the additive was based on the relative comparison of engine particulate emissions (PND, mass and particle size distribution) produced with and without the additive. In order to ensure the quality of data and have a valid comparison, the instrumentation, instrumentation settings, probes and sample line conditions were maintained constant for tests conducted with and without the additive. To the extent possible, all other parameters believed to influence engine particulate emissions were controlled or studied to investigate their potential impact on emissions to avoid misattribution of an effect (positive or negative) to the additive. Careful consideration was given to uncontrollable factors such as atmospheric conditions and different fuel batches. Although it was preferable to use the same fuel for engine tests with and without the additive, it was not possible in most situations. However, fuel samples were chemically characterized and potential influence of sulfur and aromatics on the resultant particulate emissions were investigated. Emissions measurements were performed for at least five engine conditions to study the effects of the additive throughout the entire operating range of the engine. A large number of tests were performed in each of the emissions campaigns to provide sufficient data for statistical analysis and assessment of the experimental uncertainty. The test plans were developed by the AF in collaboration with Boeing and UMR, and reviewed with officials from the program office (T-43 tests) or base officials (Randolph and Barksdale AFB).

Appendix D: Health and Safety Plan

For these demonstrations, fuel handlers employed the same safety practices used for handling conventional JP-8 since there are no know safety issues associated with handling JP-8+100. Prior to starting the tests, scientists, engineers and technicians were provided with verbal safety procedures by the facility or base personnel. Test site practices, procedures and exit routes in case of an emergency were discussed. These helped ensure the safety of all test personnel during and after the tests were completed. Safety and logistic issues associated with the T-43 tests at Randolph AFB were addressed in the test plan. A copy is provided below.

Safety and Logistic Issues T43 tests at Randolph AFB

- Two aircraft will be made available.
    - Both engines of both aircraft must be run with JP-8+100 for approximately four hours prior to any flights with JP-8+100. The engine fuel filters shall be inspected/changed before the conversion to JP8+100, after four hours of engine ground runs/operation, and again at the end of the test program.
- Randolph AFB personnel (engine operator) and the Test Director and will hold safety briefings prior to the beginning of each test session.
- Test power settings have been selected to keep the engines from running in any time limited operational envelope. (Specify engine run time at test points, i.e. 3 minutes, 4 minutes etc.)
- The sampling probes will be placed no closer than six inches from the engine exhaust duct plane.
- All other test equipment will be positioned no closer than ten feet from the aircraft wing tip.
- Sample lines will be run from the probe under the aircraft to the test trailer. The lines will held in position with sand bags (UMR to provide). No test equipment will be placed in front of the aircraft. Both engines shall be run during all tests.
- The aircraft will be fully fueled prior to the beginning of each test session.
- UMR will provide their electric power supply.
- C4e Inc. will provide the water tanks to cool the sampling probes.
- UMR to provide sampling probe, base, and lead ballast.
- Randolph AFB to provide communication head sets and “Y” cords for test trailer and “spotters”.
- Randolph AFB to provide a forklift for moving the probe assembly, base and lead ballast.
- Randolph AFB to provide the JP8+100 test fuel from a single supply tank for this test.
- T-43 APU clearance to run with JP8+100 have been obtained and documented with TPCRs. These TPCRs are available upon request.
- Aircraft Engine and APU Fuel Filters
    1. JP-8 baseline engine runs may be performed using existing installed filters.
    2. Prior to operating the aircraft on JP-8+100, replace engine and APU fuel filters with new filters.
    3. After the first JP-8+100 ground test, and prior to first flight with JP-8+100, replace the engine and APU fuel filters.

4. Operate the aircraft using JP-8+100 using the following engine and APU fuel filter replacement and inspection schedule:
   a) 8-10 hours of operation with JP8+100; replace engine and APU filters.
   b) Thereafter, every 8-10 hours of operation with JP-8+100, inspect the engine and APU filters and replace as needed.

Acronyms

ACC – Air Combat Command
AETC - Air Education and Training Command
AF – Air Force
AFRL – Air Force Research Laboratory
AFRL/PRTG – Fuels Branch, Turbine Engine Division, Propulsion Directorate, AFRL
CNC – Condensation Nuclei Counter
DMA – Differential Mobility Analyzer
EI - Emissions Index {pollutant mass (g) ÷ fuel mass used (kg)}
EPA – Environmental Protection Agency
ESTCP – Environmental Security Technology Certification Program
GC/MS – Gas Chromatography/Mass Spectrometry
ICAO - International Civil Aviation Organization
IR – Infrared
LPC – Laser Particle Counter
NAAQS - National Ambient Air Quality Standards
NIST - National Institute of Standards and Technology
PAH – Polycyclic Aromatic Hydrocarbons
PM10 – Particulate Matter equal or smaller than 10 microns diameter
PM2.5 – Particulate Matter equal or smaller than 2.5 microns diameter
PND – Particle Number Density (number of particles per cm^3)
SPO – System Program Office
TEOM – Tapered Element Oscillating Microbalance
THC – Total Unburned Hydrocarbons
UMR – University of Missouri-Rolla
UTC – Universal Technology Corporation
UTRC – United Technologies Research Center
WRDC – Wright Research Development Center